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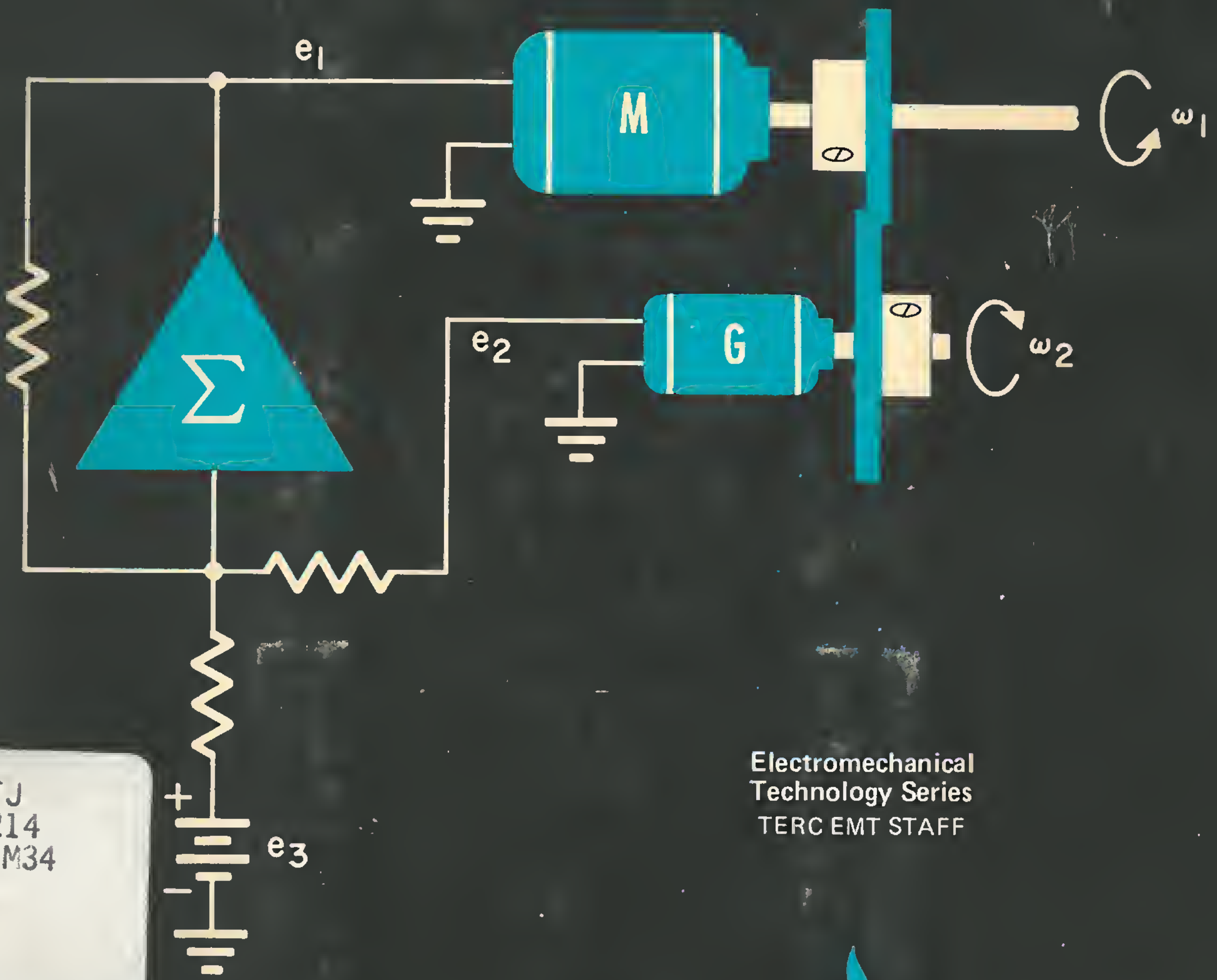

Electromechanical
Technology Series
TERC EMT STAFF

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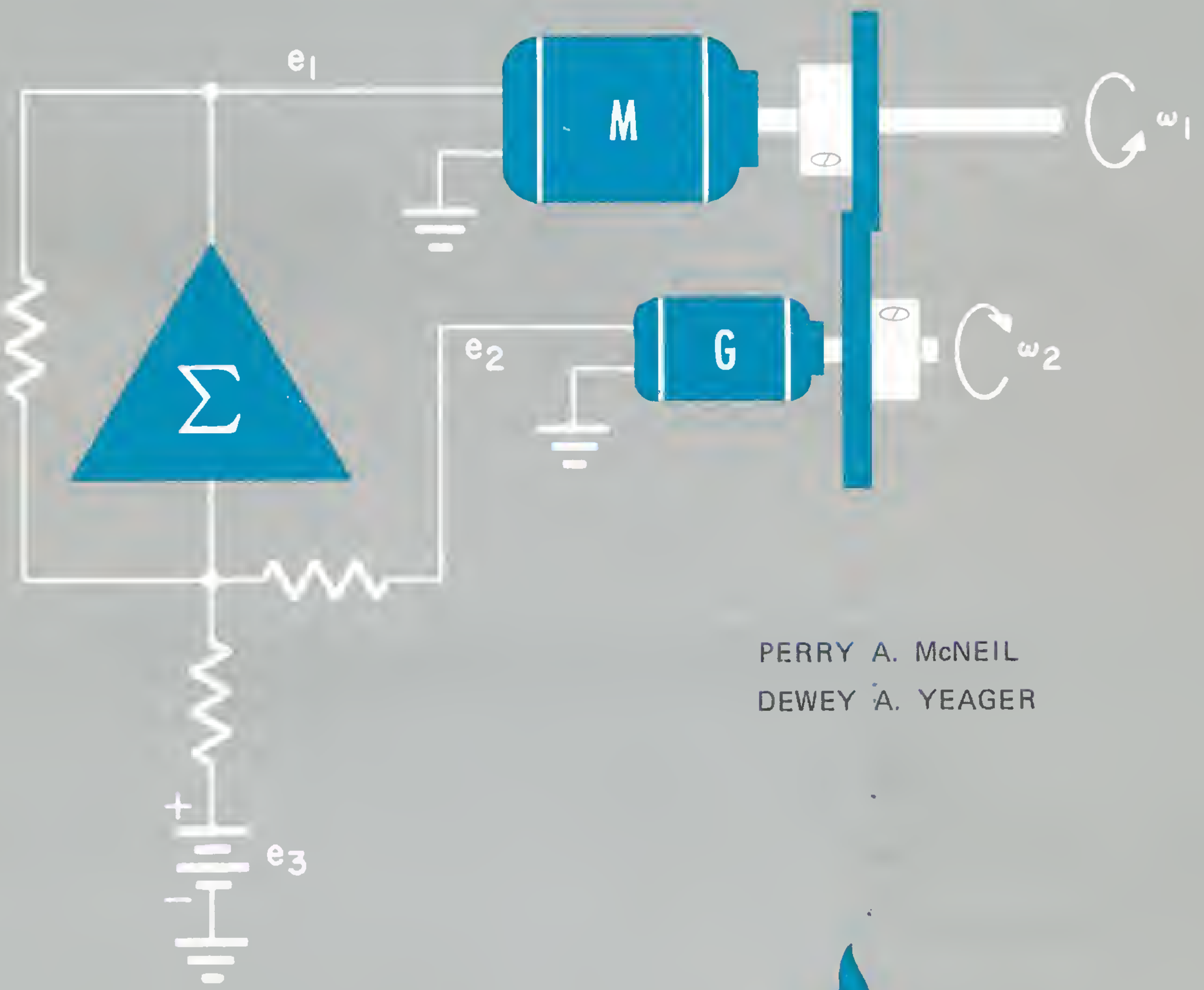

PERRY A. McNEIL
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Foreword

The marriage of electronics and technology is creating new demands for technical personnel in today's industries. New occupations have emerged with combination skill requirements well beyond the capability of many technical specialists. Increasingly, technicians who work with systems and devices of many kinds — mechanical, hydraulic, pneumatic, thermal, and optical — must be competent also in electronics. This need for combination skills is especially significant for the youngster who is preparing for a career in industrial technology.

This manual is one of a series of closely related publications designed for students who want the broadest possible introduction to technical occupations. The most effective use of these manuals is as combination textbook-laboratory guides for a full-time, post-secondary school study program that provides parallel and concurrent courses in electronics, mechanics, physics, mathematics, technical writing, and electromechanical applications.

A unique feature of the manuals in this series is the close correlation of technical laboratory study with mathematics and physics concepts. Each topic is studied by use of practical examples using modern industrial applications. The reinforcement obtained from multiple applications of the concepts has been shown to be extremely effective, especially for students with widely diverse educational backgrounds. Experience has shown that typical junior college or technical school students can make satisfactory progress in a well-coordinated program using these manuals as the primary instructional material.

School administrators will be interested in the potential of these manuals to support a common first-year core of studies for two-year programs in such fields as: instrumentation, automation, mechanical design, or quality assurance. This form of *technical core* program has the advantage of reducing instructional costs without the corresponding decrease in holding power so frequently found in general core programs.

This manual, along with the others in the series, is the result of six years of research and development by the *Technical Education Research Centers, Inc.,* (TERC), a national nonprofit, public service corporation with headquarters in Cambridge, Massachusetts. It has undergone a number of revisions as a direct result of experience gained with students in technical schools and community colleges throughout the country.

Maurice W. Roney

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Preface

Technology, by its very nature, is a laboratory-oriented activity. As such, the laboratory portion of any technology program is vitally important. This material is intended to provide a meaningful experience with servomechanisms for students of modern technology.

The topics included provide exposure to basic principles of synchromechanisms, as well as an introduction to analog and digital control systems.

The sequence of presentation chosen is by no means inflexible. It is expected that individual instructors may choose to use the materials in other than the given sequence.

The particular topics chosen for inclusion in this volume were selected primarily for convenience and economy of materials. Some instructors may wish to omit some of the exercises or to supplement some of them to better meet their local needs.

The materials are presented in an action-oriented format combining many of the features normally found in a textbook with those usually associated with a laboratory manual. Each experiment contains:

1. An INTRODUCTION which identifies the topic to be examined and often includes a rationale for doing the exercise.
2. A DISCUSSION which presents the background, theory, or techniques needed to carry out the exercise.
3. A MATERIALS list which identifies all of the items needed in the laboratory experiment. (Items usually supplied by the student such as pencil and paper are normally not included in the lists.)
4. A PROCEDURE which presents step-by-step instructions for performing the experiment. In most instances the measurements are done before calculations so that all of the students can at least finish making the measurements before the laboratory period ends.
5. An ANALYSIS GUIDE which offers suggestions as to how the student might approach interpretation of the data in order to draw conclusions from it.
6. PROBLEMS are included for the purpose of reviewing and reinforcing the points covered in the exercise. The problems may be of the numerical solution type or simply questions about the exercise.

Students should be encouraged to study the text material, perform the experiment, work the review problems, and submit a technical report on each topic. Following this pattern, the student can acquire an understanding of, and skill with, basic control systems that will be extremely valuable on the job. For best results, these students should have a sound background in technical mathematics (algebra, trigonometry, and introductory calculus.)

These materials on basic control systems comprise one of a series of volumes prepared for technical students by the TERC EMT staff at Oklahoma State University, under the direction of D.S. Phillips and R.W. Tinnell. The principal authors of these materials were Perry R. McNeil and D.A. Yeager.

An *Instructor's Data Guide* is available for use with this volume. Mr. Robert L. Gourley was responsible for testing the materials and compiling the instructor's data book for them. Other members of the TERC staff made valuable contributions in the form of criticisms, corrections, and suggestions.

It is sincerely hoped that this volume as well as the other volumes in this series, the instructor's data books, and the other supplementary materials will make the study of technology interesting and rewarding for both students and teachers.

THE TERC EMT STAFF

Contents

experiment 1 THE SYNCHRO TRANSMITTER

INTRODUCTION. One of the most common classes of control devices are those called synchro-mechanisms or synchros. In this experiment we will examine some of the properties of one type of synchro, the synchro transmitter.

DISCUSSION. You will find the general class of control elements called synchros in many different applications of automatic control. They are used with other components to form complex control systems and they are used by themselves in groups to form complete data transmission systems. In this latter use there is always an angular mechanical input that positions a shaft. The mechanical input is transmitted as electrical information and eventually is converted back to a mechanical output at a remote location.

In this discussion, we will examine the class of devices referred to as synchro transmitters, generators, or sometimes as torque transmitters. The transmission of data may be accomplished with either 60-Hz or 400-Hz energy.

Basically, a synchro is composed of a rotor that revolves inside of three coils physically displaced 120 degrees from one another. The electrical connection to the power source is supplied to the synchro through the slip rings shown at the left of figure 1-1. Two of the three stator windings which are 120 degrees apart can also be seen. The rotor turns on ball bearings to reduce friction.

Two alternate schematics for a synchro transmitter are shown in figure 1-2.

For purposes of explaining the operation of a synchro, figure 1-2(A) will best serve our needs. When we get to the point of drawing systems and circuits, figure 1-2(B) will be easier and simpler to use.

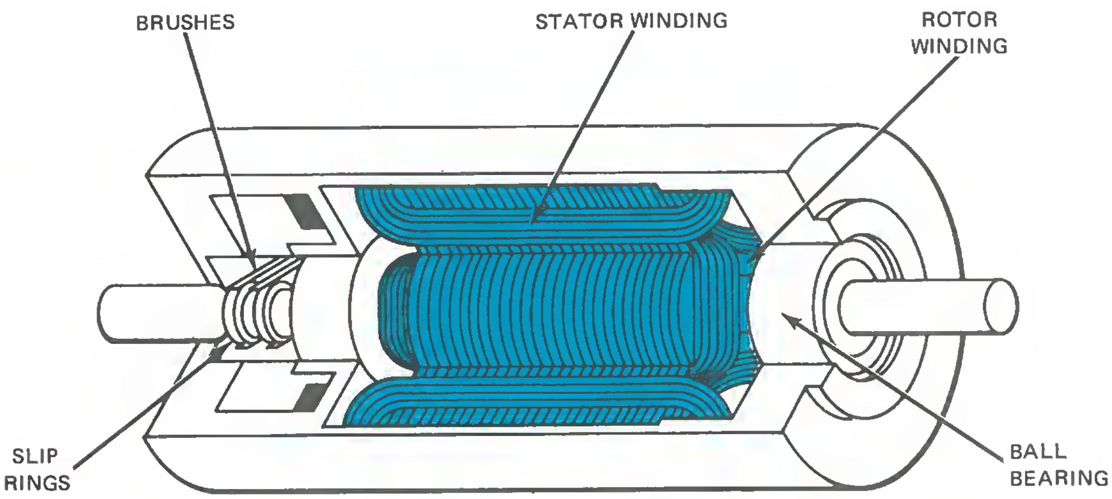


Fig. 1-1 Cutaway of a Synchro

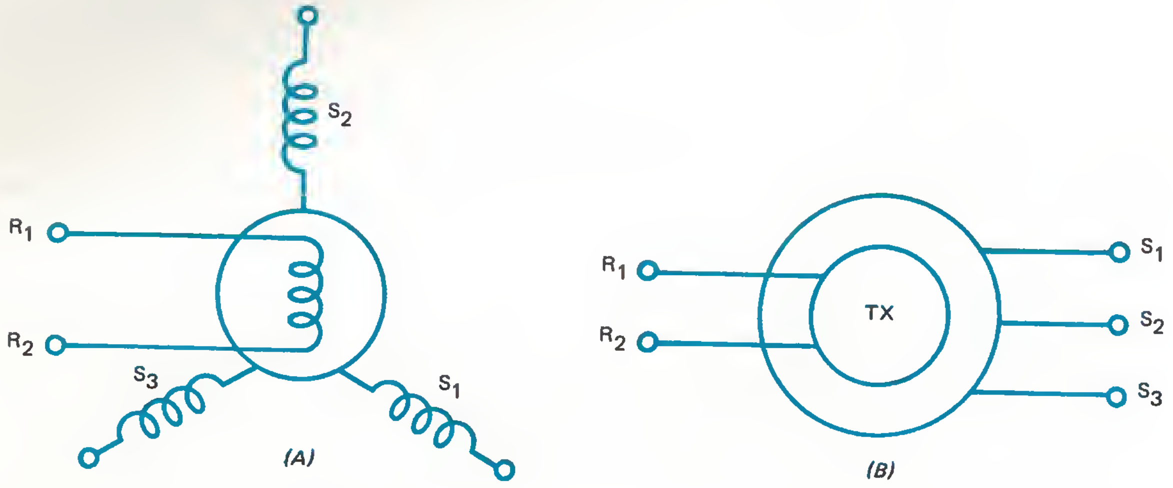


Fig. 1-2 Schematic Representation of a Synchro

Remembering that the rotor (R_1 to R_2) is free to be rotated, let's consider the circuit in figure 1-3.

As the rotor is shown in the figure, there will be a maximum voltage induced into stator number 2 and a value less than this will be induced into stators 1 and 3. If the turns ratio between the rotor and the stators is 1:1, the stator voltage of number 2 will be approximately the same as the rotor voltage. As the rotor is turned in a clockwise direction, the voltage in stator 2 will decrease until the rotor has gone through 90 degrees, at which time the value of the voltage will be zero. If we remember that we get no coupling of magnetic fields when two coils are perpendicular to one another, zero volts is to be expected for a rotation of 90 degrees. Now as we continue to turn the rotor in a clockwise direction, the stator 2 voltage will increase, in a negative direction, as the opposite end of the coil will now be coming up toward S_2. (See figure 1-4.) We will obtain the maximum negative voltage at 180°, or when the rotor has made one half of a revolution. If we con-

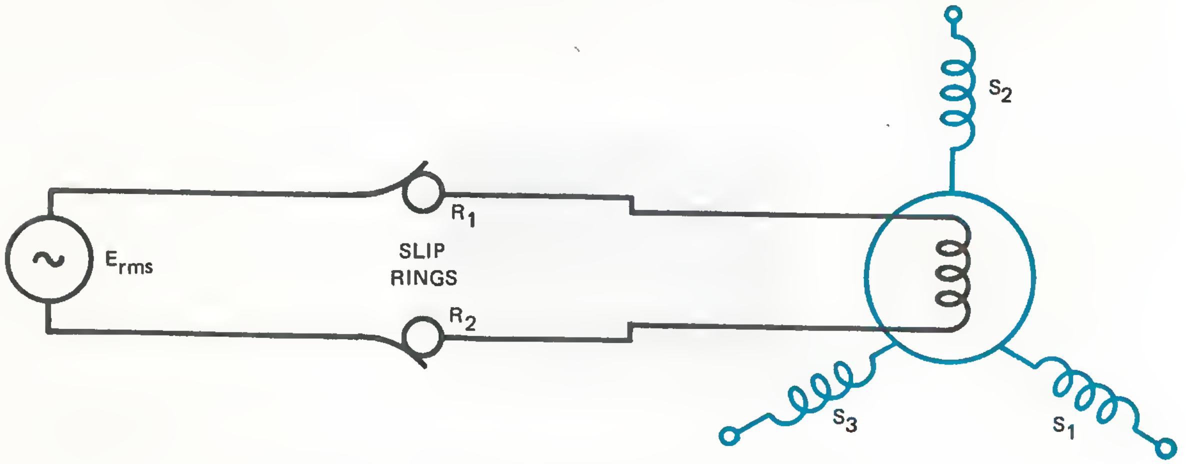


Fig. 1-3 Power Source Connected to a Synchro

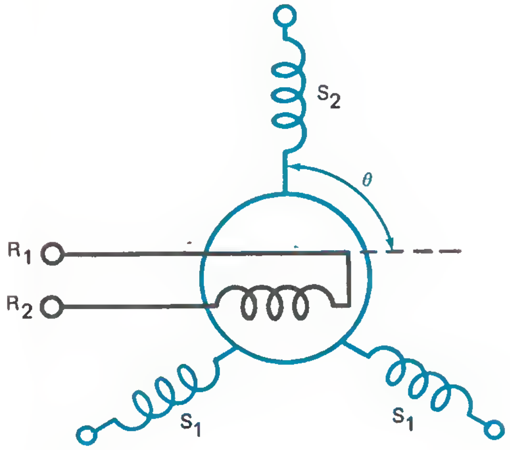


Fig. 1-4 Clockwise Rotation of the Rotor

tinue the rotation for another 180 degrees making a complete cycle of the rotor, the graph shown in figure 1-5 could be plotted.

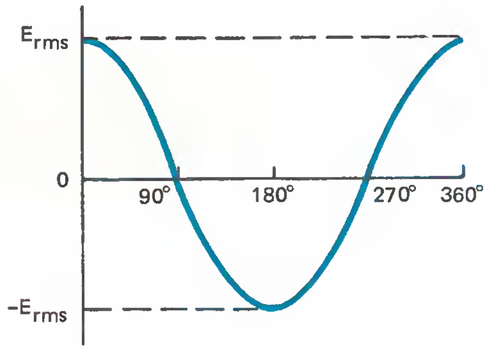


Fig. 1-5 One Cycle of S_2 Voltage

If we examine the plot of this stator voltage we can readily write a mathematical equation for the voltage as a function of the rotor shaft angle.

$$\boxed{E_{S2} = kE_R \cos\theta} \qquad (1.1)$$

where k is a proportionality constant that relates the turns ratio between the rotor and the stators. One of the most common values of turns ratio is a 2.2:1 step-down ratio between the rotor and stator so that k = 1/2.2. If the rms value of E_R is 115 volts, then $E_{S2\,max}$ would be 52 volts rms.

Considering that S_1 is 120 degrees in space ahead of S_2, and S_3 is 240 degrees ahead, the following relationships will hold for stator voltages 1 and 3:

$$\boxed{E_{S1} = kE_R \cos(\theta - 120^\circ)} \qquad (1.2)$$

$$\boxed{E_{S3} = kE_R \cos(\theta - 240^\circ)} \qquad (1.3)$$

Note that when the rotor has been turned 30 degrees, E_{S1} will be zero, and when it has been turned 150 degrees, E_{S3} will be zero. In synchro discussions, don't assume we are operating with a polyphase motor: we are not, there is only one phase applied to the input.

When we get ready to measure the stator voltages to verify the relationships discussed above, we will find that this can not be done without tearing into the device or setting up a special measuring circuit. In figure 1-6 the three resistors are all the same size, but of high enough ohmic value, about 5,000 ohms, to limit excessive current flow.

If the resistors are all the same size, the stator voltages can be measured across the corresponding resistors. With this circuit we can observe and record the individual stator voltages. Normally only the three stator leads are brought outside the machine. Therefore, without the specific measuring circuit we will only be able to measure voltages between two stator leads. We can mathematically deter-

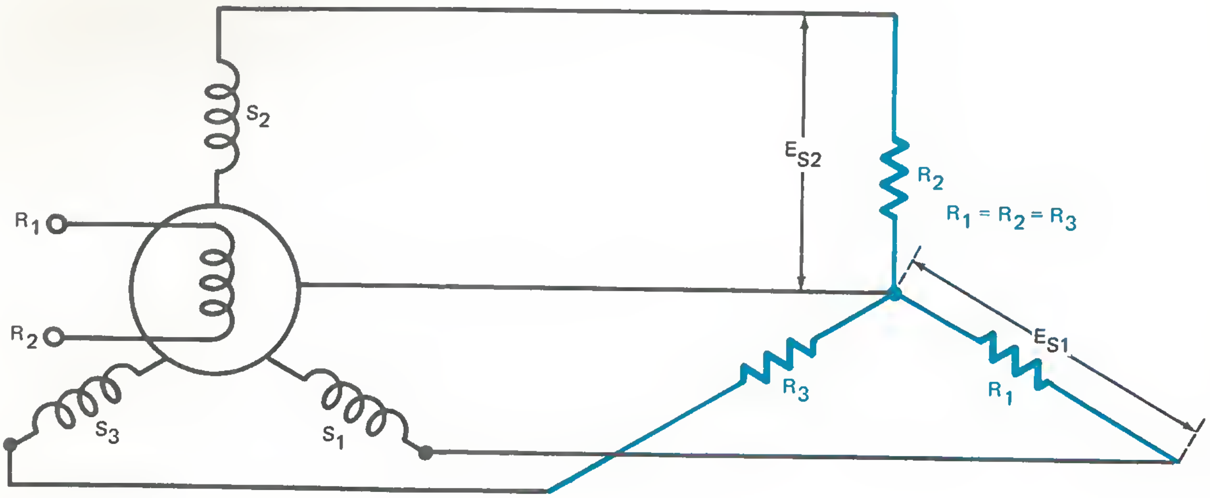


Fig. 1-6 A Loaded Synchro

mine the voltage between any two lines using one of the following relationships.

$$E_{S2\text{-}S1} = E_{S2} - E_{S1} = kE_R \cos\theta - kE_R \cos(\theta - 120°) \tag{1.4}$$
$$= kE_R [\cos\theta - \cos(\theta - 120°)]$$

$$E_{S2\text{-}S3} = E_{S2} - E_{S3} = kE_R [\cos\theta - \cos(\theta - 240°)] \tag{1.5}$$

$$E_{S3\text{-}S1} = E_{S3} - E_{S1} = kE_R [\cos(\theta - 240°) - \cos(\theta - 120°)] \tag{1.6}$$

The last item we wish to discuss in this experiment is *electrical zero*. Electrical zero occurs when the voltage between S_1 and S_3 is zero and the S_2 voltage is in phase with that at rotor terminal R_1. If we remember the physical construction of the synchro, this will occur when rotor R_1 is parallel to S_2 and the voltages in S_3 and S_1 are equal and opposite in phase. Consider the circuit shown in figure 1-7.

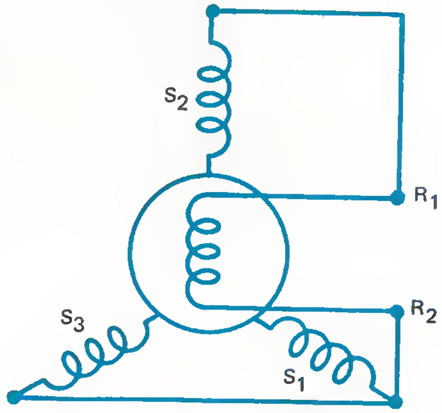


Fig. 1-7 Jumper Method of Determining Electrical Zero

We have insured zero voltage between S_1 and S_3 by connecting them together and referenced to R_2. By connecting R_1 to S_2, these two will be forced into an equal phase relationship. As the rotor is free to turn, it will automatically rotate to the above shown position. This is called the jumper method of determining electrical zero. One must not apply the full rotor voltage in this case as it could burn up the synchro.

MATERIALS

1 VOM or FEM
1 Variable transformer (0 – 130V, 60 Hz)
1 Oscilloscope
3 Resistors, 5 kΩ, 2W
1 360° disk dial
1 Synchro transmitter, type 23TX6 or equivalent with mount
1 Mechanical breadboard
2 Sheets linear graph paper

PROCEDURE

1. Using the schematic shown in figure 1-8, determine the electrical zero of the synchro transmitter. **Do not exceed a rotor voltage of 60V.**

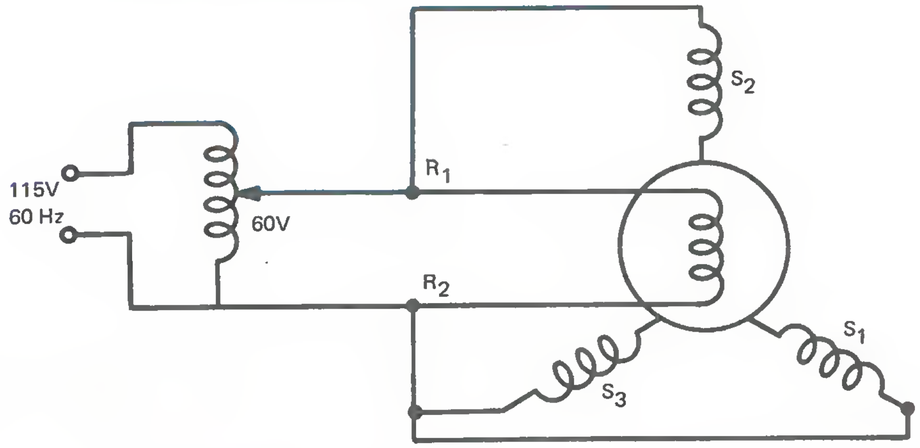


Fig. 1-8 The Electrical Zero Experimental Circuit

2. Mechanically adjust the dial on the synchro shaft until the zero mark is lined up with the electrical zero position determined in step 1.

3. Disconnect the circuit of step 1 and connect the circuit in figure 1-9.

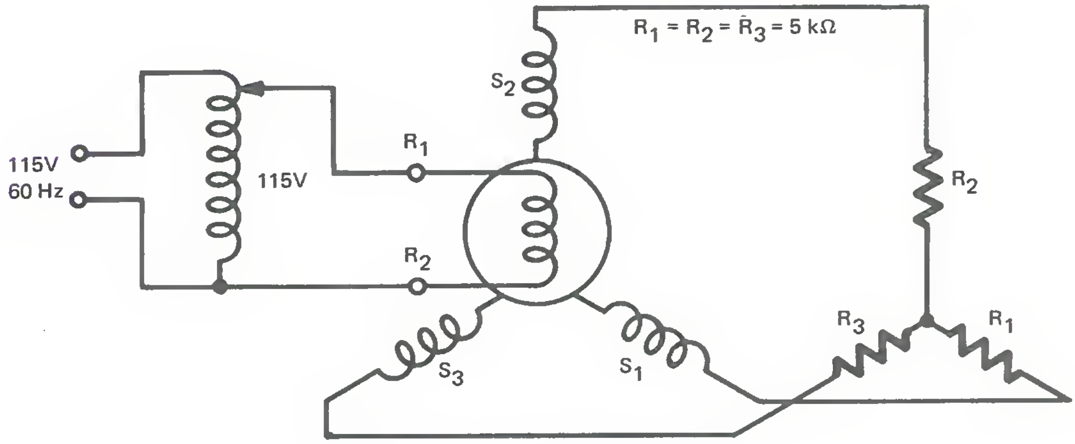


Fig. 1-9 Stator Voltage Circuit

4. Measure and record the voltage across resistor R_2 as the rotor is advanced in a clockwise direction through 360°. Take the measurements every 45°.
5. Using the oscilloscope, observe and record the wave shape of E_{R1} at 0°, 90°, 180° and 270°. Set the oscilloscope to external trigger and use R_1 as the trigger source.
6. Repeat steps 4 and 5 for resistor R_1.
7. Repeat steps 4 and 5 for resistor R_3.
8. Disconnect the three resistors from the circuit.
9. Measure and record the voltage every 45° from S_1 to S_2 as the rotor is turned clockwise through 360°.
10. Repeat step 9 for the voltage from S_3 to S_2.
11. Repeat step 9 for the voltage from S_3 to S_1.
12. Plot the data taken in steps 4, 6, and 7 on the same graph.
13. Plot the data taken in steps 9, 10, and 11 on a second graph.

ANALYSIS GUIDE. In analyzing the data from this experiment you should discuss how closely the measured stator voltages compare to what would be obtained from equations 1-1, 1-2, and 1-3. You should also discuss graphical addition of the stator voltages and the voltages measured in steps 9, 10, and 11 with the theoretical results of equations 1-4, 1-5, and 1-6.

Rotor Position	E_{R1}	E_{R2}	E_{R3}	$E_{S2\text{-}S1}$	$E_{S2\text{-}S3}$	$E_{S3\text{-}S1}$
0°						
45°						
90°						
135°						
180°						
225°						
270°						
315°						

Fig. 1-10 The Data Table

Scope Recording

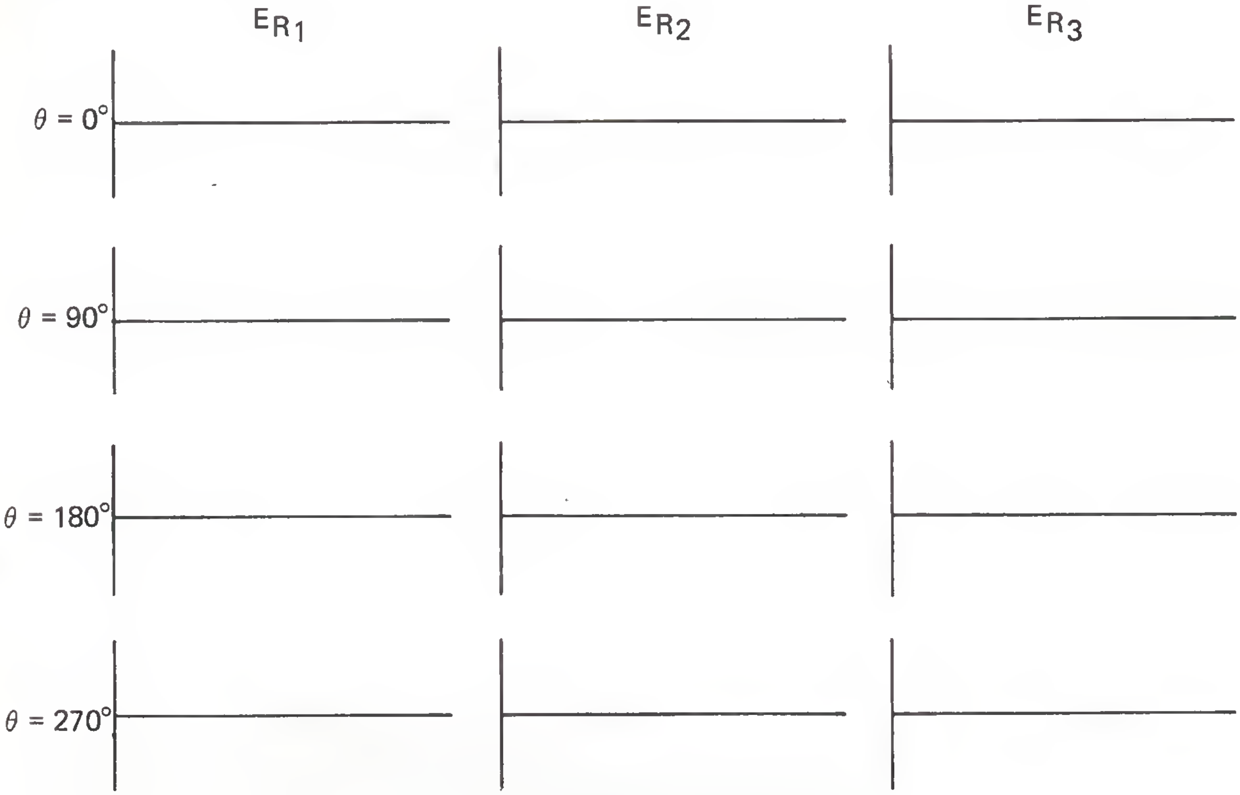


Fig. 1-10 The Data Tables (Cont'd)

PROBLEMS

1. If you were restricted to using a voltmeter and not connecting any wires together, describe a method for determining the electrical zero of a synchro.
2. What was the turns ratio of this synchro?
3. Why was only 60 volts applied to the rotor in step 1?

experiment 2 *SYNCHRO DATA TRANSMISSION SYSTEMS*

INTRODUCTION. Synchros are very often used in pairs to form a data transmission system. The synchro sending the information is called a transmitter and the other, a receiver. In this experiment we shall examine the characteristics of such a system.

DISCUSSION. The basic difference between a synchro transmitter and receiver lies in the amount of damping built into the rotor. This damping may be accomplished by a large plate attached to one end of the rotor. Figure 2-1 shows a receiver rotor with such an *inertia damper* on the left side of the rotor reducing the tendency to overshoot a predetermined position. That is, it tends to reduce oscillation.

The electrical schematic for the receiver will look exactly like that of a transmitter. Figure 2-2 shows two alternate schematics for a synchro receiver.

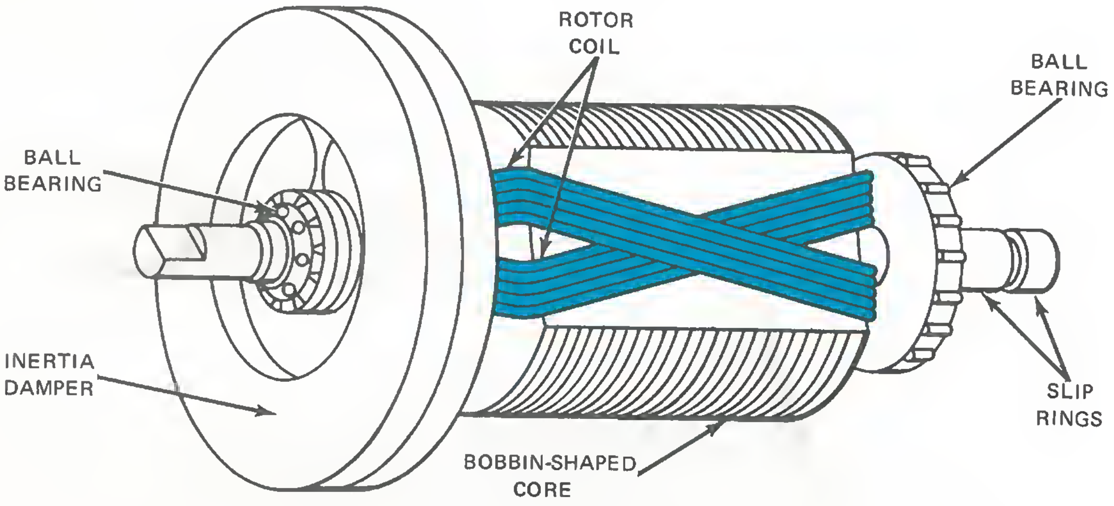


Fig. 2-1 Rotor of Synchro Receiver

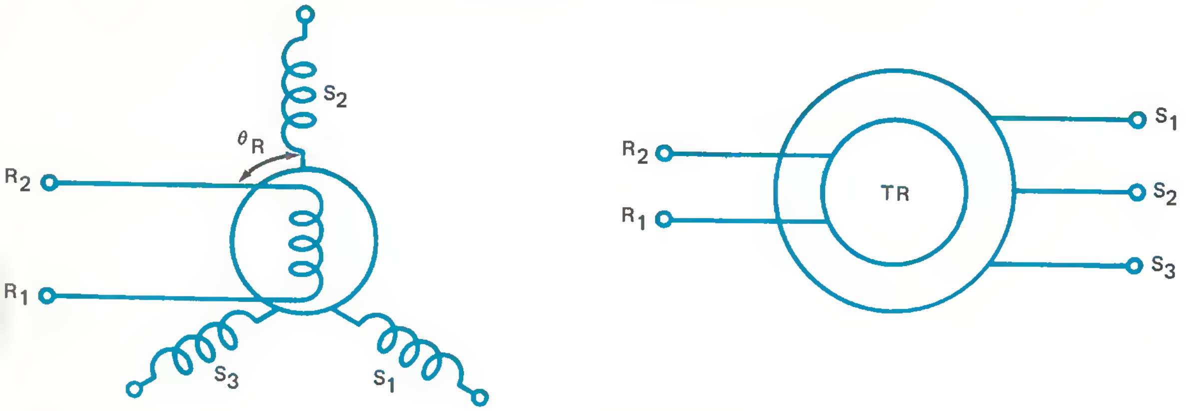


Fig. 2-2 Schematic Symbols for a Synchro Receiver

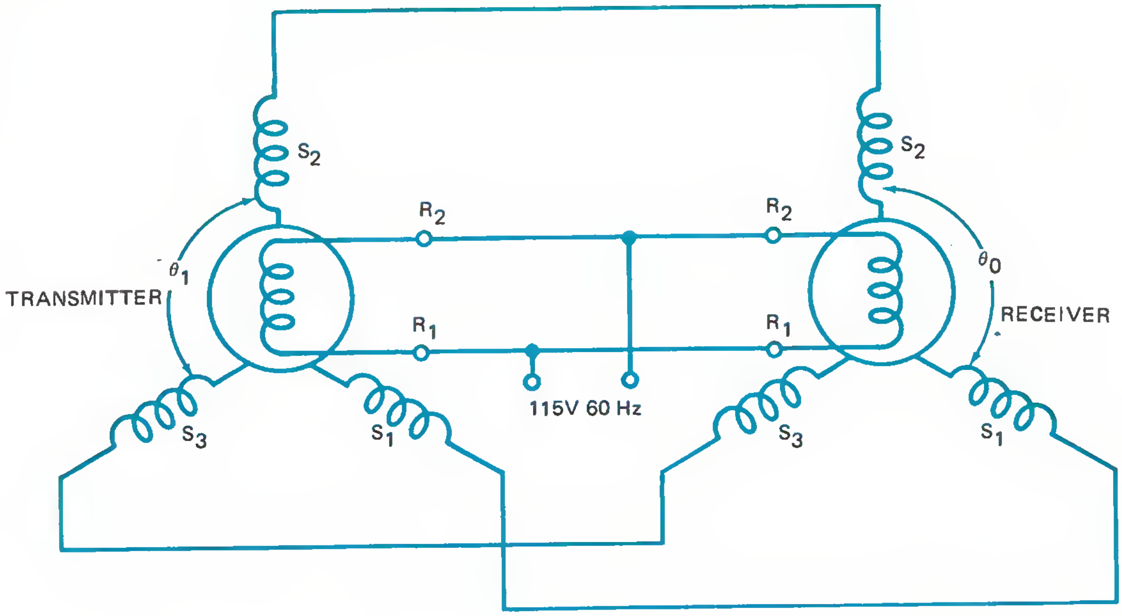


Fig. 2-3 A Synchro Pair

In the case of a transmitter, we apply a mechanical input to the rotor and get an electrical output from the stators, or in other words, we have a mechanical-to-electrical transducer.

In the case of the receiver, the electrical input is applied to the stators and a mechanical output is obtained from the rotor. So the synchro receiver can be considered an electrical-to-mechanical transducer. In both cases, an electrical power source is applied to the rotor.

Let's consider the operation of the circuit shown in figure 2-3. In this case the rotors of a transmitter and a receiver are both connected to a 60-Hz line.

In the position the rotors are shown, there will be a maximum voltage induced into stator S_2 of the transmitter and a lesser value induced into stators S_1 and S_3. These same voltages will then be transmitted to the receiver stators. Since its rotor is in the same position as the transmitter's, there will be no tendency for the receiver rotor to turn due to the interaction of the magnetic fields. Remember that the receiver rotor will have the same magnetic field as the transmitter rotor.

If the transmitter rotor is turned 30 degrees clockwise, this will induce voltages into the stators that can be determined by

$$\boxed{E_{S_2} = kE_R \cos\theta} \qquad (2.1)$$

$$\boxed{E_{S_1} = kE_R \cos(\theta - 120^\circ)} \qquad (2.2)$$

$$\boxed{E_{S_3} = kE_R \cos(\theta - 240^\circ)} \qquad (2.3)$$

If the turns ratio is 2.2:1 and $E_R = 115V$, then $E_{S_2} = 45V$, $E_{S_1} = 0V$, $E_{S_3} = -45V$. We can determine the resultant voltage vector of the stator field by vector addition. The voltages are directly proportional to the direction and magnitude of the magnetic fields.

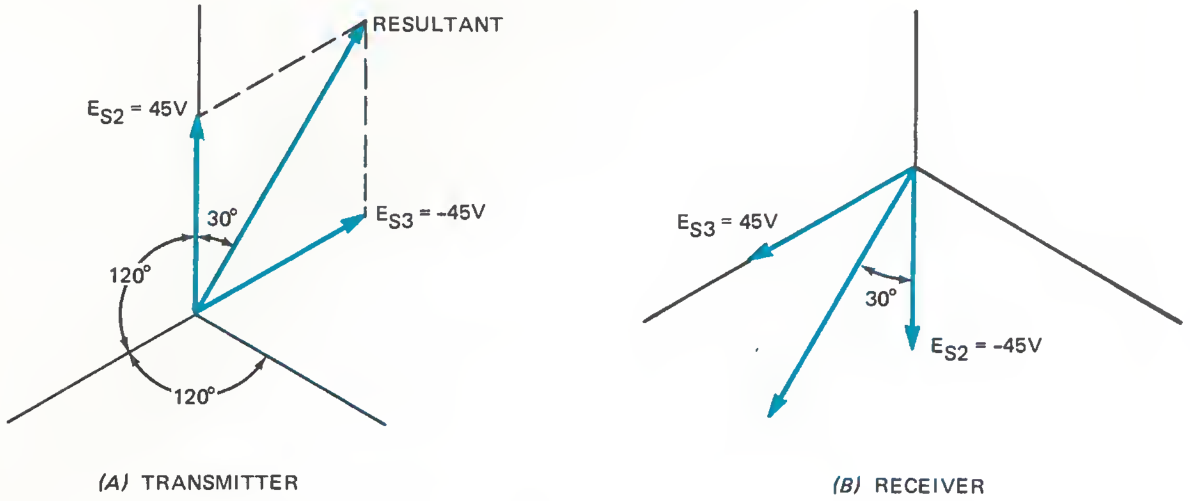


Fig. 2-4 Stator Magnetic Fields

According to Lenz's law, the voltages at the receiver stators are equal and opposite to the transmitter's. Let's now consider the resultant magnetic polarities in the stator and rotor windings of both the transmitter and the receiver. (See figure 2-5.)

The magnetic polarities of the transmitter stators are opposite the rotor's because an induced voltage always opposes the applied voltage. The receiver stator polarities are opposite to those of the transmitter stators because they are connected in series. We can then see that the resultant flux in the receiver stators will be such that the receiver rotor is turned 30 degrees clockwise. Indeed, for this particular connection, the receiver will follow the transmitter, degree for degree of rotation.

If the leads to the receiver rotor were reversed as shown in figure 2-6, the receiver will be 180 degrees ahead of the transmitter. If we refer back to figure 2-5, we can see that the receiver rotor polarities would be reversed,

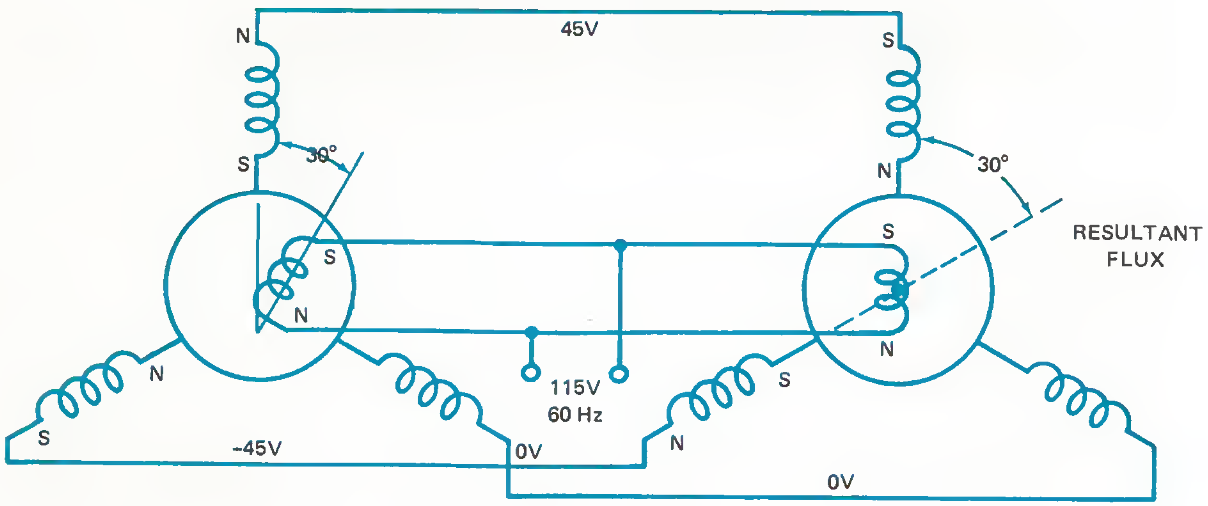


Fig. 2-5 Magnetic Polarities

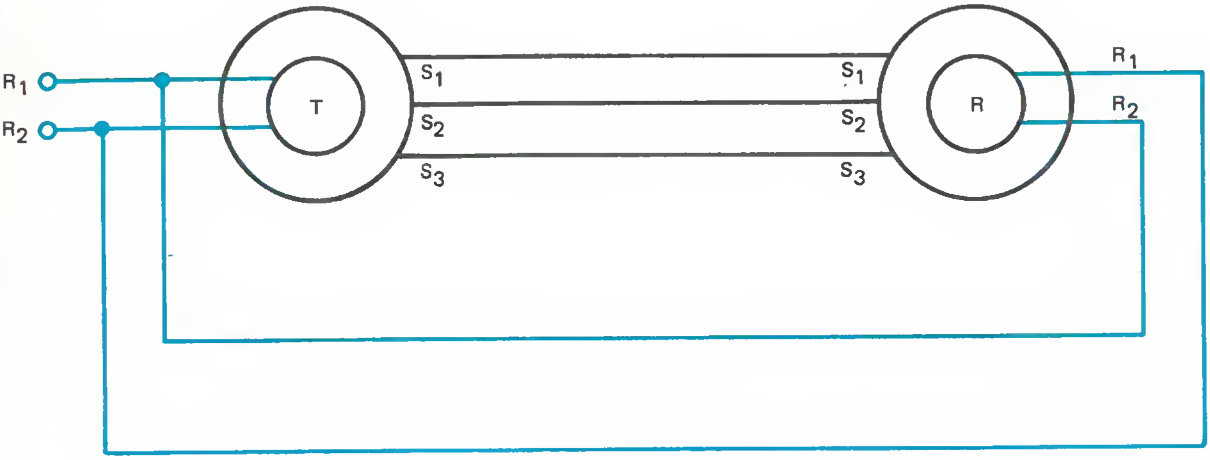


Fig. 2-6 Rotor Leads Reversed

but the stators would remain the same. This, of course, would cause the receiver to turn in just the opposite direction compared to the transmitter. A vector analysis would also verify that the receiver is 180 degrees ahead of the transmitter.

There are several other possible connection arrangements. In this experiment we shall investigate the effect of several different stator connections as well as the two rotor arrangements described above. In all such cases we can determine the resultant fields by vector analysis if necessary.

As in the case of the transmitter it is always necessary to know where the receiver's electrical zero is located. The jumper method can be used to determine the electrical zero of a receiver in the same manner as is done with a transmitter.

Another technique for determining electrical zero is called the *voltmeter method.* Electrical zero occurs when the voltage between S_1 and S_3 is zero and the voltage at S_2 is in phase with that at R_1. We can quite readily determine these voltage readings with a voltmeter as shown in figure 2-7.

There will, of course, be two positions 180 degrees apart, at which V_1 will be zero. The correct position will occur when V_2 reads *less than* the line voltage. At the incorrect position, V_2 will read more than the line voltage.

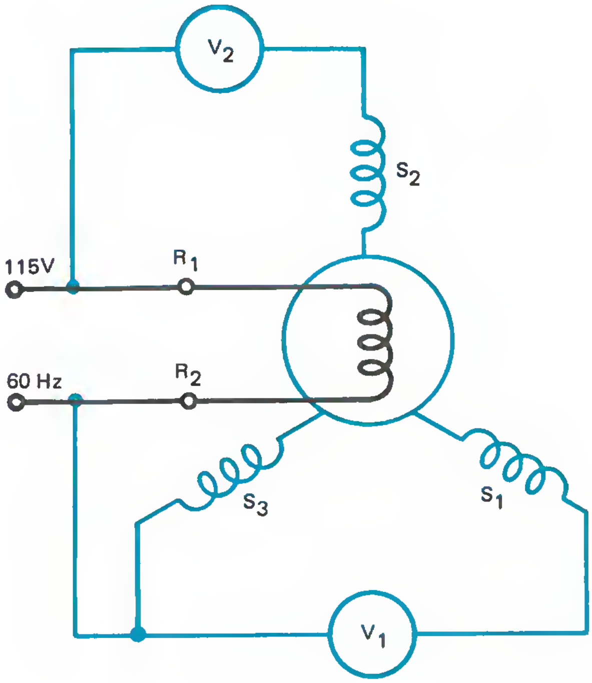


Fig. 2-7 Voltmeter Method for Determining Electrical Zero

MATERIALS

- 2 VOMs or FEMs
- 1 Synchro transmitter, type 23TX6 or equivalent with mount
- 1 Synchro receiver, type 23TR6 or equivalent with mount
- 1 Variable transformer (0 - 130V, 60 Hz)
- 2 360° disk dials
- 1 Spring balance
- 1 Lever arm (1 in.)
- 1 Spring balance post
- 1 Mechanical breadboard

PROCEDURE

1. Using the voltmeter method, determine the electrical zero of both the transmitter and the receiver.
2. Adjust each of the synchro dials so that the zero mark is lined up with the electrical zero position determined in step 1.
3. Connect the circuit shown in figure 2-8.

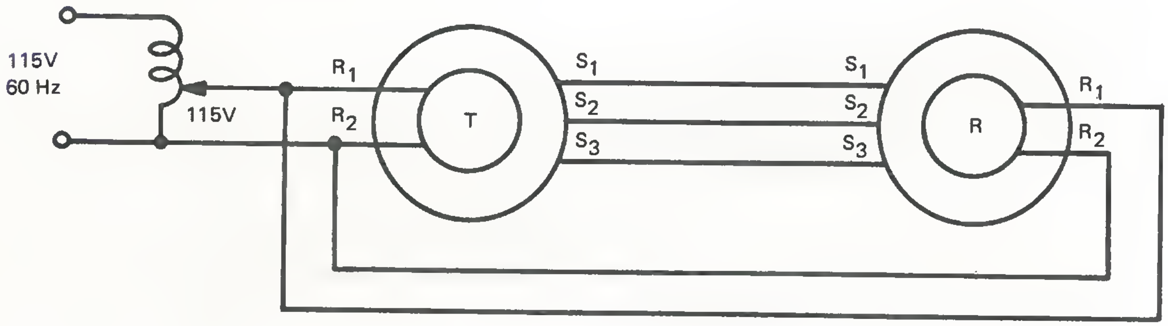


Fig. 2-8 First Experimental Circuit

4. Starting with the transmitter rotor set to 0°, observe and record the position of the receiver as the transmitter is rotated clockwise through 180°. Record your observations every 45°.
5. Again with the transmitter set at 0°, observe and record the position of the receiver as the transmitter is rotated counterclockwise through 180°. Record your observations every 45°.
6. Reverse the rotor leads of the receiver and repeat steps 4 and 5.
7. Connect the circuit of figure 2-9 and repeat steps 4 and 5.

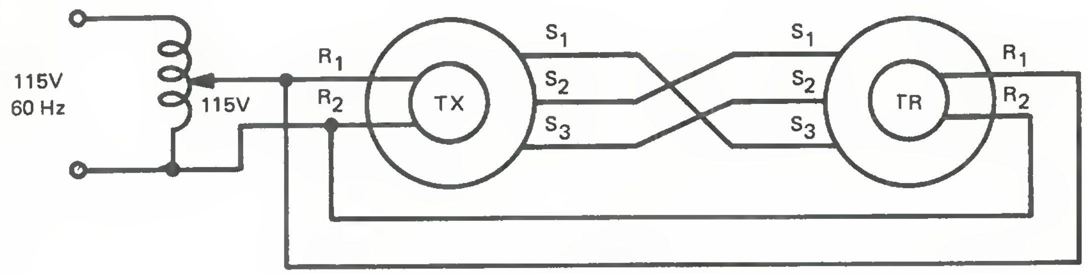


Fig. 2-9 Second Experimental Circuit

8. Connect the circuit of figure 2-10 and repeat steps 4 and 5.

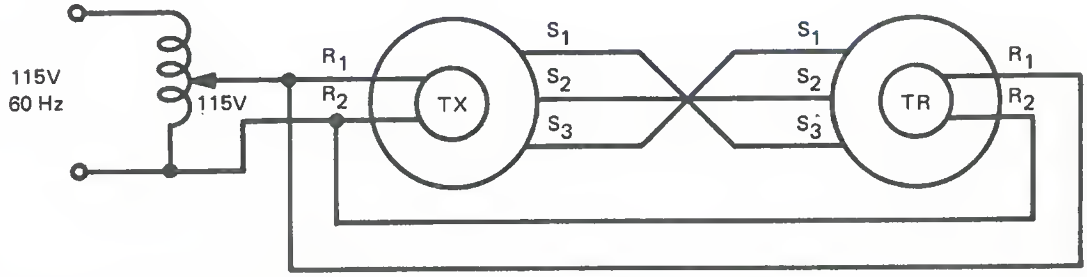


Fig. 2-10 Third Experimental Circuit

9. Connect the circuit of figure 2-11 and repeat steps 4 and 5.

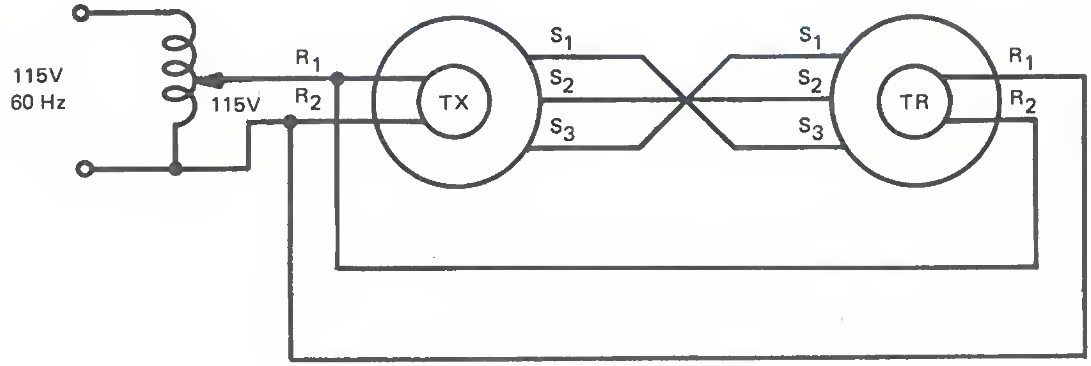


Fig. 2-11 Fourth Experimental Circuit

10. Re-connect the circuit of figure 2-8. Measure and record the static torque of the receiver for a transmitter setting of 45°. Use a spring balance and lever to make this measurement.

11. Plot on the same graph the data collected in steps 4, 5, 6, 7, 8, and 9.

ANALYSIS GUIDE. In analyzing the data from this experiment you should discuss why there were or were not errors in the recorded angles of the receiver rotor. You should also do a vector analysis of each experimental circuit to see if the displacement angles you measured were correct. Was the recorded torque of sufficient magnitude that it could perform a useful function?

Transmitter Rotor - θ_T	Receiver Steps 4&5 - θ_R	Receiver Step 6 - θ_R	Receiver Step 7 - θ_R	Receiver Step 8 - θ_R	Receiver Step 9 - θ_R
0°					
45°					
90°					
135°					
180°					
-45°					
-90°					
-135°					
-180°					

Receiver Torque ______________________

Fig. 2-12 The Data Table

PROBLEMS

1. What is the rotor angle of a transmitter if the S_1 voltage is -9V and the S_3 is -40V?
2. If the transmitter rotor of figure 2-10 is set to 46°, what will be the position of the receiver rotor?

experiment 3 THE SYNCHRO CONTROL TRANSFORMER

INTRODUCTION. In many control systems there is a need for a device that will detect any error between the mechanical position of the input and that of the output. One device that is very commonly used in this type of error detection is a synchro control transformer. We shall examine the characteristics of a control transformer in this experiment.

DISCUSSION. Schematically, a synchro control transformer looks exactly like a synchro transmitter or receiver. Whereas the synchro receiver is an electrical-to-mechanical transducer, the control transformer is an electrical-to-electrical transformer. A control transformer is shown in figure 3-1. The inputs to the stators normally come from a transmitter as shown in figure 3-1.

The rotor of the control transformer is not connected to the line voltage as is done with both the transmitter and the receiver. The output is simply the induced voltage that results from the position of the transformer rotor with respect to the voltages present in the stators. The need for such a device arises when the torque available from a synchro receiver is not sufficient to move an output device. In that case, the output of the synchro control transformer is fed into an amplifier which supplies a motor which drives the output load. An example of such a system is shown in figure 3-2.

To see how the system shown in figure 3-2 works, we must first examine what causes the output of the control transformer to change. If we re-examine the schematic shown in figure 3-1, we observe that the voltage in both S_2 stators will be at its maximum value.

The voltage in both the S_1s and S_3s will be one half this value but of opposite polarity. Since the control transformer rotor is at right angles to S_2, there will be no voltage induced from that stator. Stators 1 and 3 will each

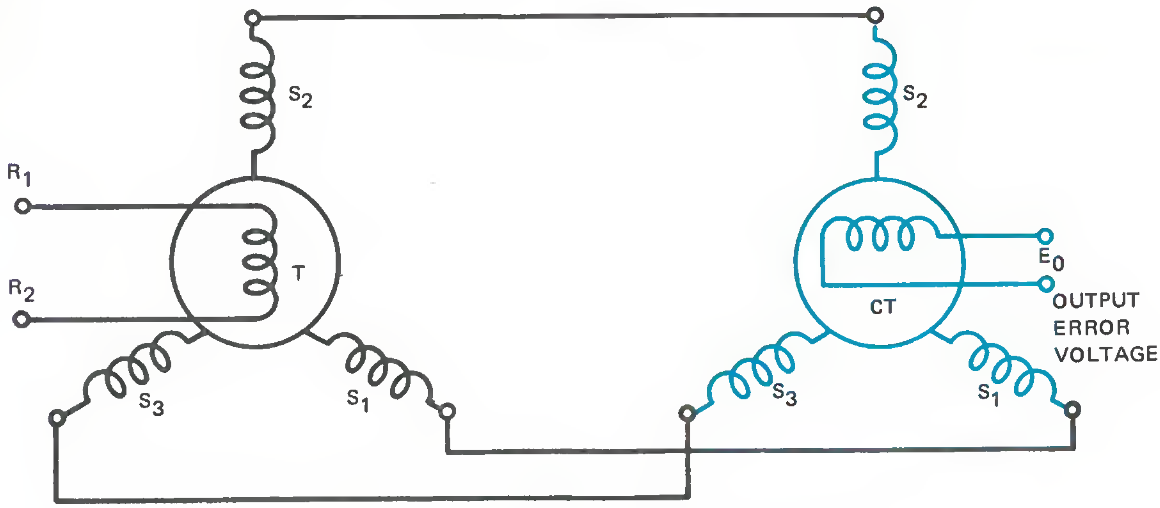


Fig. 3-1 Transmitter-Control Transformer Pair

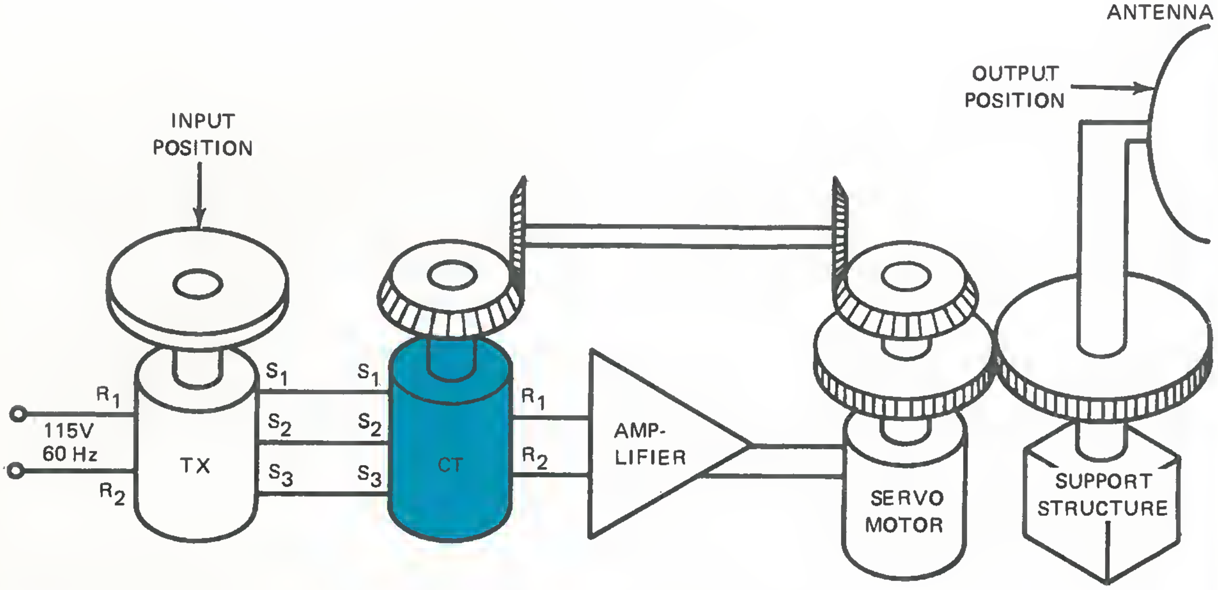


Fig. 3-2 A Position Control System

induce a voltage of equal amplitude into the rotor but they will be of opposite polarity and will cancel. At this position the output voltage will be zero. If we were to rotate the control transformer rotor 180 degrees, the output would again be zero as it would again be perpendicular to S_2. Therefore, if the transmitter is at electrical zero, the output of the transformer will be zero only if it is perpendicular to S_2. This is the electrical zero position of the control transformer. To physically determine the electrical zero of a control transformer, the system indicated in figure 3-3 can be used.

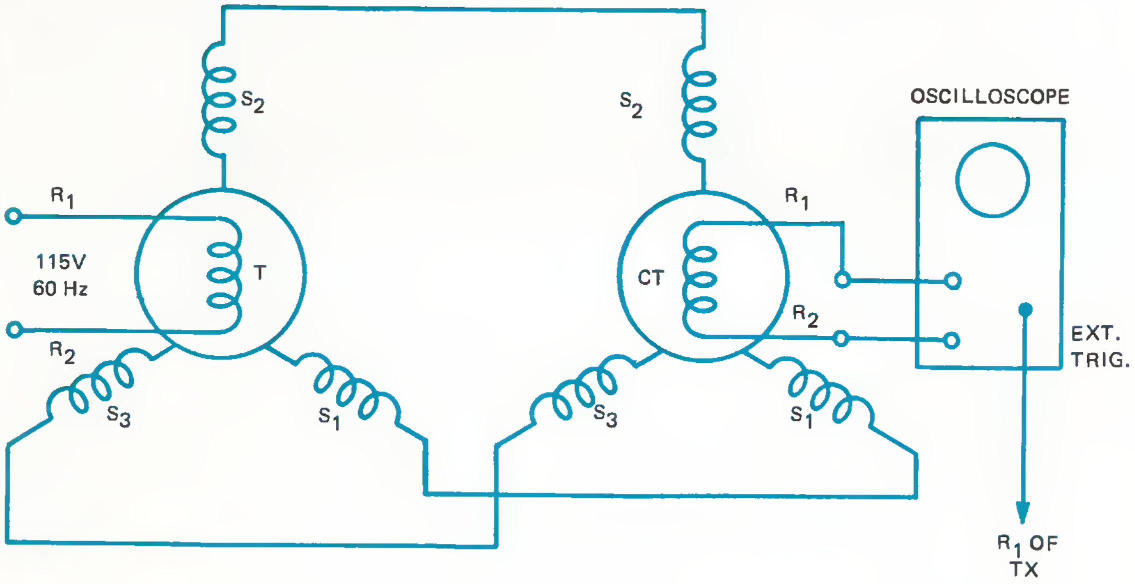


Fig. 3-3 Determining Electrical Zero of a Control Transformer

First we set the transmitter to its electrical zero position and then set the control transformer to one of the zero output positions. Now we rotate the transformer shaft clockwise and observe the phase of the output voltage. If it is in phase with the transmitter, this is the correct zero position. If it is 180 degrees out of phase, then the other zero output is the correct electrical zero position.

If the transmitter is rotated clockwise 30 degrees, the voltages in S_1 and S_3 of the transformer will no longer be of equal amplitude and of opposite polarity. As a result, the output of the transformer will indicate a measureable voltage which represents a *difference* in shaft angles of 30 degrees. The maximum value of voltage will be induced in the transformer rotor when the transmitter has been rotated 90 degrees. At this point the stator voltage S_2 will be zero and stators S_1 and S_3 will be at one half their maximum voltage value but of the same polarity. With this in mind we can see that the output of the control transformer will be given by

$$E_o = E_{max} \sin(\Theta - \theta) \qquad \textbf{(3.1)}$$

where $(\Theta - \theta)$ is the difference in angular position of the two shafts while E_{max} is a function of the turns ratio of the synchro and the applied voltage.

In some applications it is advantageous to use the phase of the output rather than the amplitude. The phase angle of the output is normally referenced to the voltage applied to the transmitter rotor. The output is either in phase with the transmitter or 180 degrees behind it. If the rotor of the transformer is moved clockwise, the output will be in phase. Conversely, if the rotation of the transmitter is in a clockwise direction, there will be a 180-degree phase differential between the reference voltage and the control transformer output.

Now as we re-examine figure 3-2 we can obtain some insights as to how this system functions. When a mechanical input is applied to the transmitter, an output error voltage will be applied to the input of the amplifier. The amplifier will then have an output which will turn on the motor, causing the antenna to turn as well as feeding back a mechanical input to the control transformer. This action will continue until the rotor of the transformer has the same position as the transmitter's rotor. At that instant the output will be zero and the motor will be turned off. In this fashion the antenna will be positioned to the same position as the transmitter shaft which may be located a considerable distance away.

MATERIALS

- 1 VOM or FEM
- 1 Synchro transmitter, type 23TX6 or equivalent with mount
- 1 Synchro control transformer, type 23CT6 or equivalent with mount
- 1 Variable transformer (0 – 130V, 60 Hz)
- 2 360° disk dials
- 1 Mechanical breadboard
- 1 Oscilloscope
- 1 Sheet linear graph paper

PROCEDURE

1. Determine the electrical zero of the control transformer.
2. Adjust the dial so that the zero mark is lined up with the position determined in step 1.

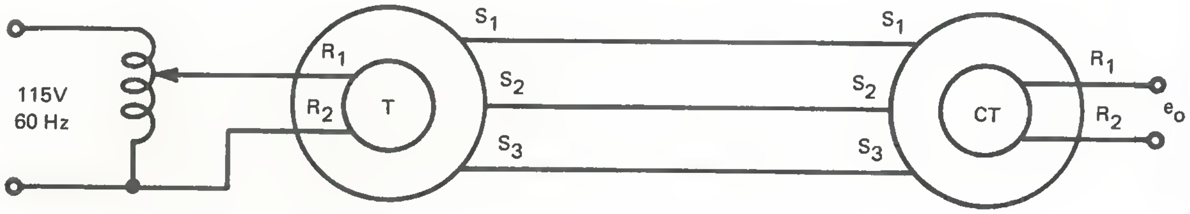


Fig. 3-4 The Experimental Circuit

3. Connect the circuit shown in figure 3-4.
4. Set the control transformer to zero degrees and record the output voltage (E_o) as the transmitter is rotated through ±180°. Take your readings every 60°.
5. Using an oscilloscope, record the phase (+ for in-phase and out-of-phase) for each of the readings in step 4. Set the scope to trigger externally and use R_1 of the transmitter as the trigger source.
6. Repeat steps 4 and 5 with the CT set to 30°.
7. Repeat steps 4 and 5 with the CT set to 330°.
8. Plot on the same graph the data collected in steps 4, 5, 6, and 7.

ANALYSIS GUIDE. In analyzing the data from this experiment you should discuss how closely the graphs plotted compare with equation 3.1. You should also discuss why there were or were not significant differences in the three graphs.

	0°		30°		330°	
Transmitter Angle Θ_i	Transformer Output e_o		Transformer Output e_o		Transformer Output e_o	
	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
0°						
60°						
120°						
180°						
-60°						
-120°						
-180°						

Fig. 3-5 The Data Table

PROBLEMS

1. Is there a linear portion of the output of a control transformer? Explain.
2. Could the output phase angle be referenced to another voltage instead of that at R_1?
3. In figure 3-2, if the transmitter is turned 30° counterclockwise, in what direction will the antenna turn? *Assume a positive voltage will cause the motor to turn clockwise.*

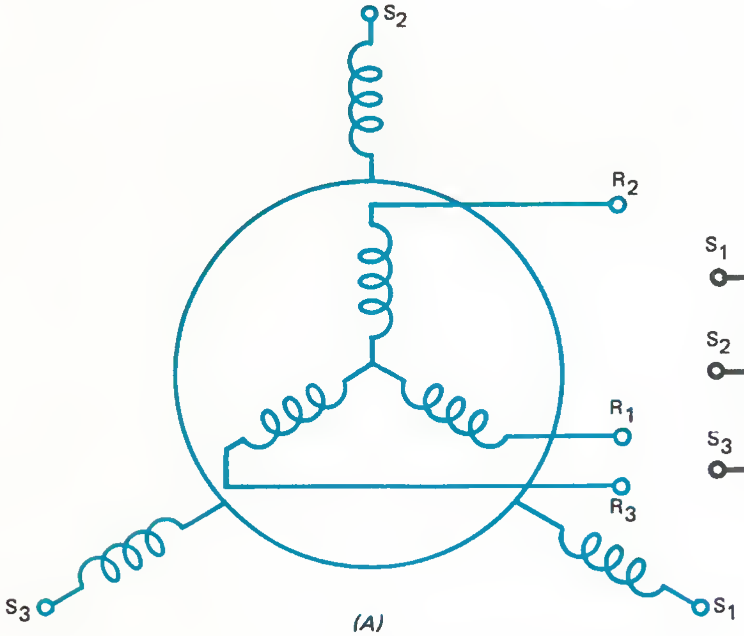
experiment 4 THE SYNCHRO DIFFERENTIAL

INTRODUCTION. In many control systems there is a requirement for information concerning the relative mechanical position of two different shafts or indicators. In this experiment we shall investigate the characteristics of a device that will indicate relative positions, the synchro differential.

DISCUSSION. In some applications it is necessary to transmit the angular difference of two shafts in the form of an electrical information in such a fashion that a receiver will position itself to this difference. The device often used to accomplish this is a differential synchro transmitter.

The stators of a synchro differential are electrically identical to those of a synchro transmitter; that is, there are three stators connected in a wye configuration. The rotor, however, is very different from a synchro transmitter as it, too, has three windings connected in a wye separated by 120°. Two alternate schematic symbols for a synchro differential are shown in figure 4-1. The coils of the rotor are wound in such a fashion that there is a one-to-one turns ratio between the stator and the rotor windings. When the maximum voltage exists in the S_2 winding, normally 52 volts, the same value will exist in rotor winding R_2 when it is parallel to S_2. These voltages are taken off the end of the shaft through three slip rings as shown in figure 4-2.

In actual practice the inputs to the stators would normally come from a synchro transmitter. The rotor windings would then be connected to the stator windings of a synchro receiver as shown in figure 4-3.



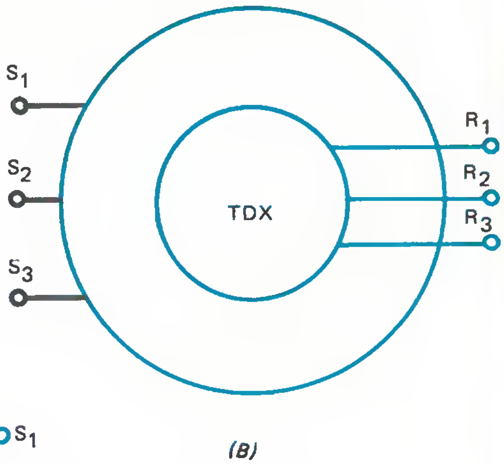


Fig. 4-1 The Synchro Differential

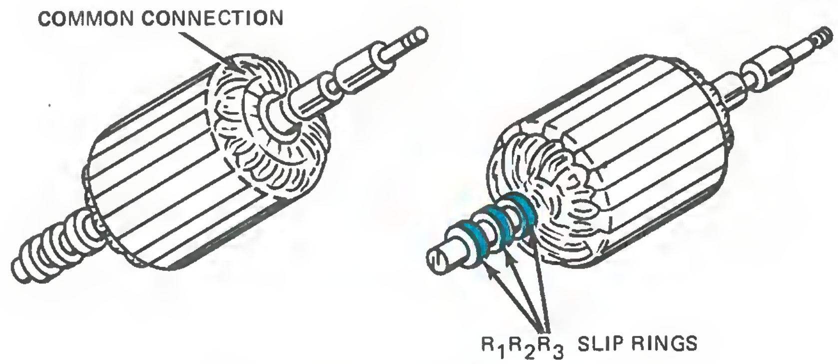


Fig. 4-2 The Differential Rotor

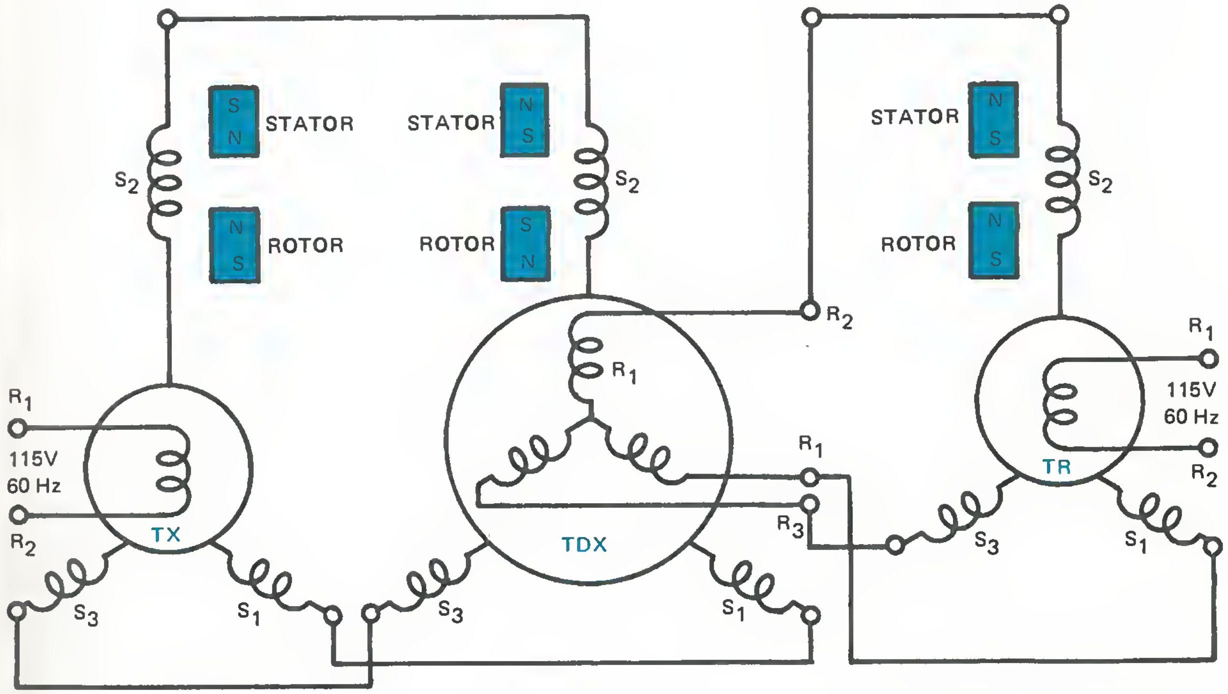


Fig. 4-3 System for Addition of Angles

To determine in what direction the rotor of the receiver will turn, we must examine the magnetic fields of each device. Starting with the transmitter, TX, the magnetic field of the rotor is such that the north pole is as shown. This field will induce a voltage into the transmitter stators such that an opposing magnetic field will result. As the stators of the differential transmitter, TDX, are in series with those of the transmitter, its field will be in the opposite direction. Accordingly, it will induce a magnetic field into the wye-connected rotor in the opposite direction. The rotor, being in series with the receiver stators, will induce a magnetic field, again opposite. The magnetic field of the receiver's rotor will be the same as the transmitter as they are connected in parallel. As can be seen, there will be an attraction between the receiver rotor and stator and the receiver will align itself at zero degrees, which is the same position as the transmitter. If we set

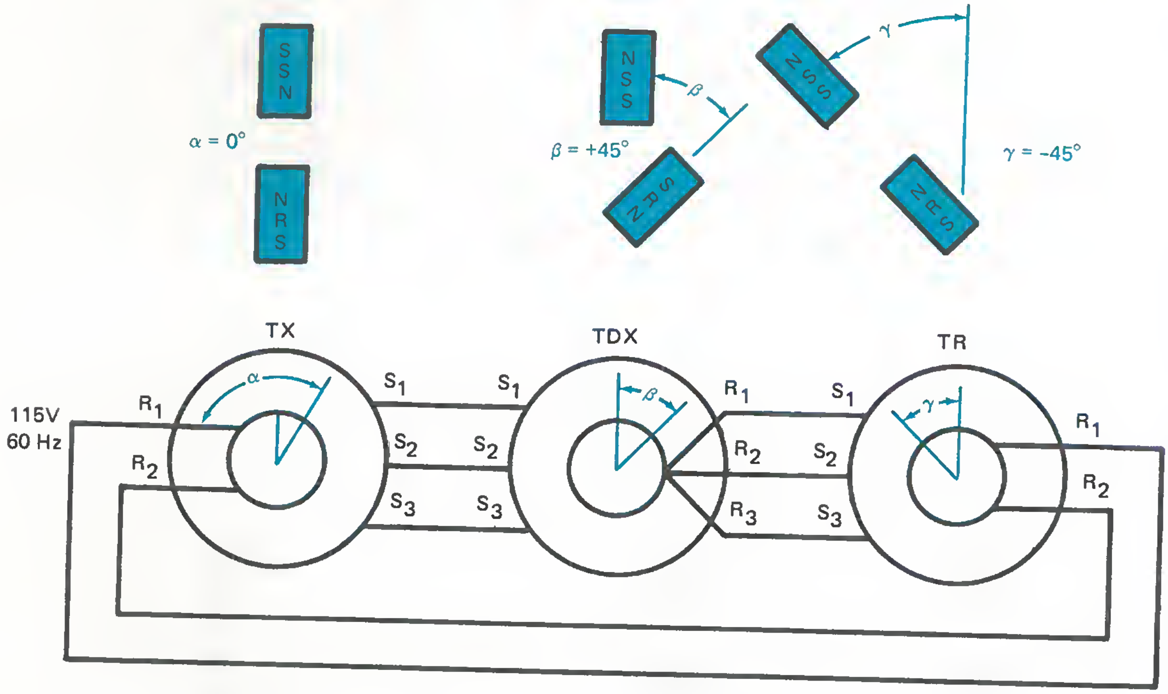


Fig. 4-4 Angular Subtraction of Shaft Position

the transmitter at zero degrees and the differential at 45° CW, let us see what happens to the receiver.

Referring to figure 4-4, in which the magnetic fields are shown above each device, S represents the stator and R the rotor fields. Since we have physically moved the differential rotor field +45°, it will induce a field into the receiver stators opposite this, or -45°. The rotor will then line up with this field and we have a net result that the receiver is positioned to the difference in the two shaft angles.

$$\boxed{\gamma = \alpha - \beta} \qquad (4.1)$$

With γ, the position of the receiver, β, the position of the differential and α, that of the transmitter.

In actual practice the differential would be connected through a mechanical linkage in such a fashion that its rotor would not be free to move once it was positioned to a particular setting.

Just as, electrically, there is no difference between a transmitter and a receiver, there is no difference between a differential transmitter and a differential receiver. If we apply electrical inputs to both the differential stator and rotor windings, the rotor will turn if it is not mechanically blocked. In those differentials that are designed to function as a receiver, there is a damping plate connected to the rotor to cut down on oscillations. Otherwise, there is essentially no difference between a differential transmitter and receiver.

You will recall for a system employing only a transmitter and a receiver, that if we reverse two leads the receiver rotor would turn exactly opposite that of the transmitter. If we reverse these same leads as shown in figure 4-5, we will obtain the addition of the shaft angles instead of the difference.

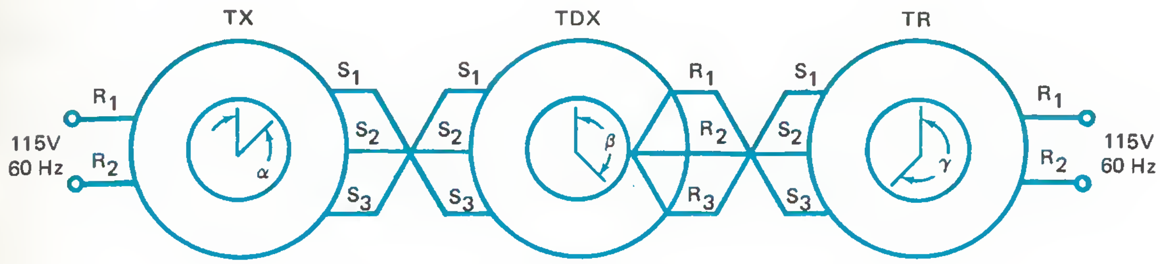


Fig. 4-5 Circuit for Addition of Shaft Angles

$$\boxed{\gamma = \alpha + \beta} \qquad (4.2)$$

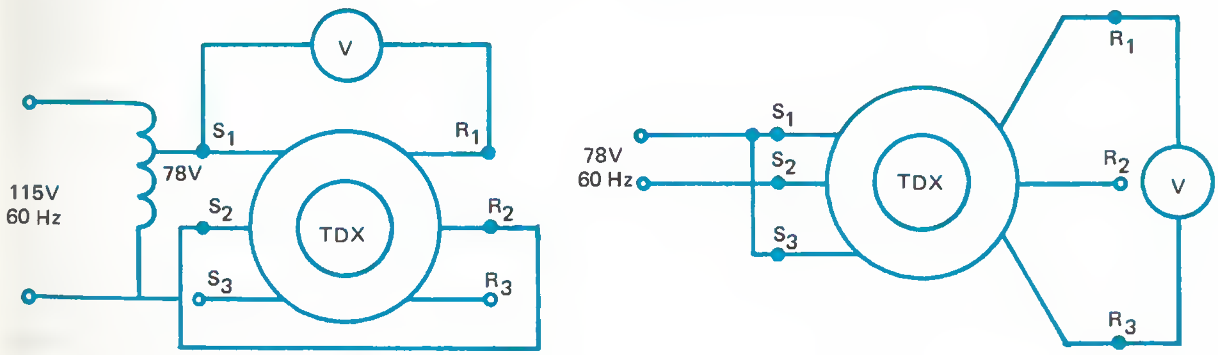
There are, of course, other ways of connecting the various stator and rotor windings. We shall investigate some of these connections in this experiment.

As with other synchro devices, we need a measuring system whereby we can determine the electrical zero of the synchro differential. Electrical zero is defined as that position of the rotor when the phase of R_2 (with respect to R_1) is the same as that of S_2, and there is zero voltage between S_1 and S_3. We can accomplish this with the connections shown in figure 4-6.

With part (A) of the figure connected, adjust the rotor for a minimum voltage indication on the voltmeter. This will be approximately electrical zero. Without moving the position of the rotor, connect the circuit shown in part (B) and adjust for zero volts on the meter. This will then be the electrical zero position of the unit.

Synchros are generally classified according to whether they have *torque* or *control* capabilities. The difference, of course, depends on whether they have the ability to position mechanical loads or not. There is a letter designation that identifies the function of the synchro as follows:

CX Control transmitter
TX Torque transmitter
TR Torque receiver
CT Control transformer
CDX Control differential transmitter
TDX Torque differential transmitter
TDR Torque differential receiver



(A) COARSE ADJUSTMENT *(B) FINE ADJUSTMENT*

Fig. 4-6 Electrical Zero of a Synchro Differential

Synchros that are built to military specifications have additional information that indicates physical size, function, and frequency of the applied voltage. For example, 23TX4 would indicate a synchro whose diameter is about 2.3 inches, functions as a torque transmitter and operates at 400 Hz. The dimension is always rounded off to the nearest tenth of an inch and 4 is used for 400 Hz while 6 designates 60 Hz.

MATERIALS

- 1 Variable transformer (0–130V, 60 Hz)
- 1 Synchro differential transmitter, type 23CDX6 or equivalent with mount
- 1 Synchro differential receiver, type 23TDR6 or equivalent with mount
- 1 Synchro transmitter type 23TX6 or equivalent with mount
- 1 Synchro receiver, type 23TR6 or equivalent with mount
- 4 360° disk dials
- 1 VOM or FEM

PROCEDURE

1. Verify that the dials on all four synchros are set to electrical zero. If they are not, adjust the dial until it is lined up with the electrical zero of the unit.

2. Connect the circuit shown in figure 4-7.

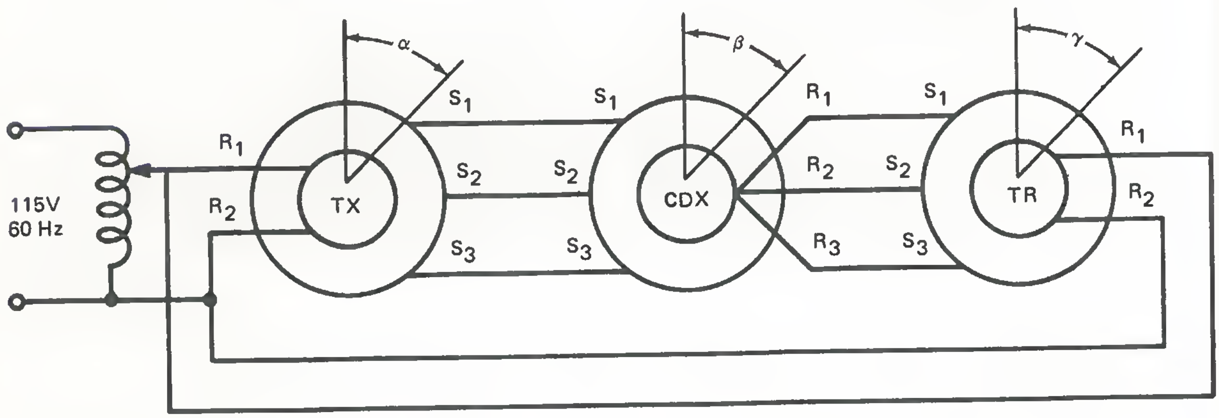


Fig. 4-7 The First Experimental Circuit

3 With the differential synchro, β, set to +45°, record the angular position of the receiver, γ, as the transmitter, α, is rotated ± 180°. Record your observations every 90° and hold the differential rotor at 45° so that it can't move.

4. Repeat step 3 with β = 270°.

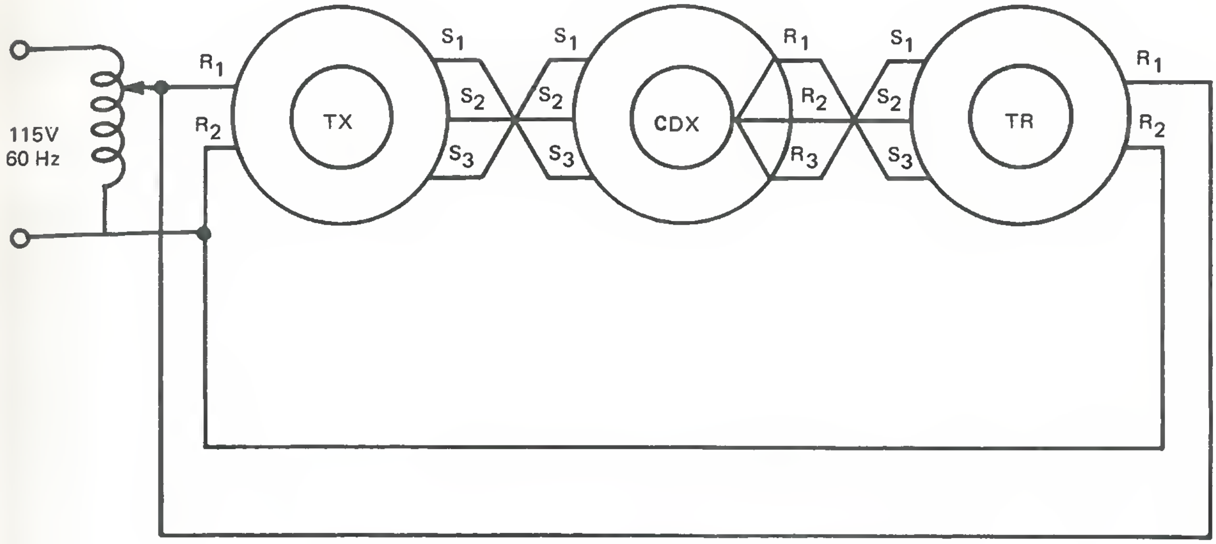


Fig. 4-8 The Second Experimental Circuit

5. Connect the circuit shown in figure 4-8 and repeat steps 3 and 4.

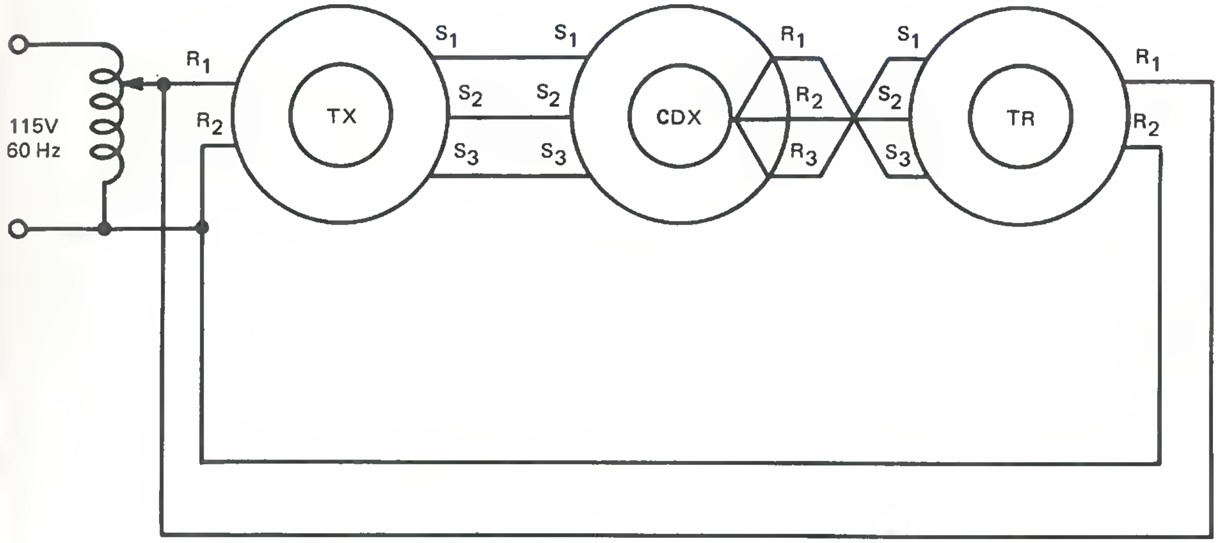


Fig. 4-9 The Third Experimental Circuit

6. Connect the circuit shown in figure 4-9 and repeat steps 3 and 4.
7. Reconnect the circuit of figure 4-7 but replace the CDX with a TDR.
8. Set the transmitter, γ, to 45° and the receiver, α, to 105° and record the position of the differential receiver, β.
9. Repeat step 7 for the values shown in the data table.

ANALYSIS GUIDE. In analyzing the data from this experiment you should verify with the magnetic fields, why the output of the system moved in the direction it did. You should discuss the difference in the output angle and the results of equation 4.1 or 4.2.

$\beta = 45°$

α	γ
0°	
90°	
180°	
-90°	
-180°	

$\beta = 45°$

α	γ
0°	
90°	
180°	
-90°	
-180°	

For Fig. 4-7

$\beta = 270°$

α	γ
0°	
90°	
180°	
-90°	
-180°	

$\beta = 270°$

α	γ
0°	
90°	
180°	
-90°	
-180°	

For Fig. 4-8

$\beta = 45°$

α	γ
0°	
90°	
180°	
-90°	
-180°	

$\beta = 270°$

α	
0°	
90°	
180°	
-90°	
-180°	

For Fig. 4-9

Steps 7 & 8

		β
45°	45°	
90°	180°	
180°	270°	
270°	360°	
360°	90°	

For Fig. 4-9

Fig. 4-10 The Data Table

PROBLEMS

1. Write a mathematical expression that describes the output of figure 4-9.
2. Write a mathematical expression for the results of steps 7 and 8 of the Procedure.
3. What is the input to the system of figure 4-7? The output?
4. Is the output of the system analyzed in step 7 mechanical or electrical information?

experiment 5 BASIC SERVOMECHANISMS

INTRODUCTION. Servomechanisms are found in all phases of modern industrial technology. In this experiment we will build a very fundamental servomechanism and examine some of its characteristics.

DISCUSSION. You are probably already familiar with one class of automatic control systems, the on-off or open loop system. An example of this type of system is an electric bathroom heater that does not have a thermostat. In figure 5-1 you can see that the only control is that obtained by an individual operating the switch.

If we add feedback to this system by replacing the switch with a thermostat, we would then have a closed loop system that automatically maintains a predetermined room temperature.

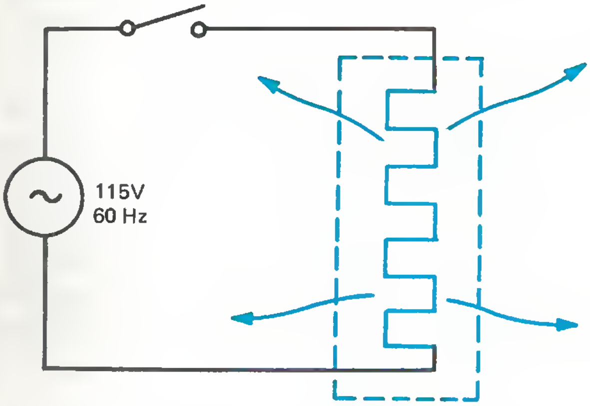


Fig. 5-1 A Basic Open Loop Control System

If a feedback control system also controls the mechanical position of an output device, it is called a *position servomechanism.* Such a system might be the one shown in figure 5-2.

The input to this system is mechanical and consists of degrees of clockwise or counterclockwise rotation of the synchro transmitter (TX) rotor shaft. The output is also mechanical and is measured in percentage of the opening of the valve. The feedback is accomplished through the gear box and a mechanical coupling to the control transformer (CT) rotor. As the CT rotor approaches the same position as the TX rotor, the input to the amplifier approaches zero and the motor shuts off. The system has reached a *null position.*

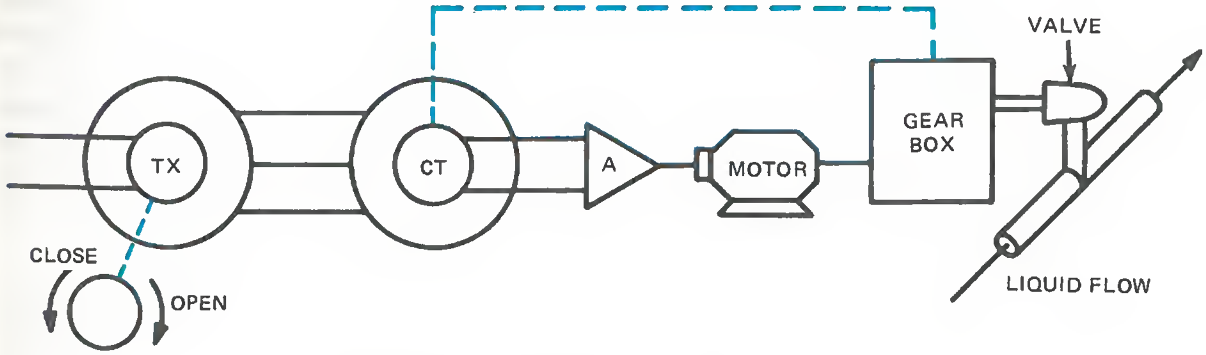


Fig. 5-2 A Position Servomechanism

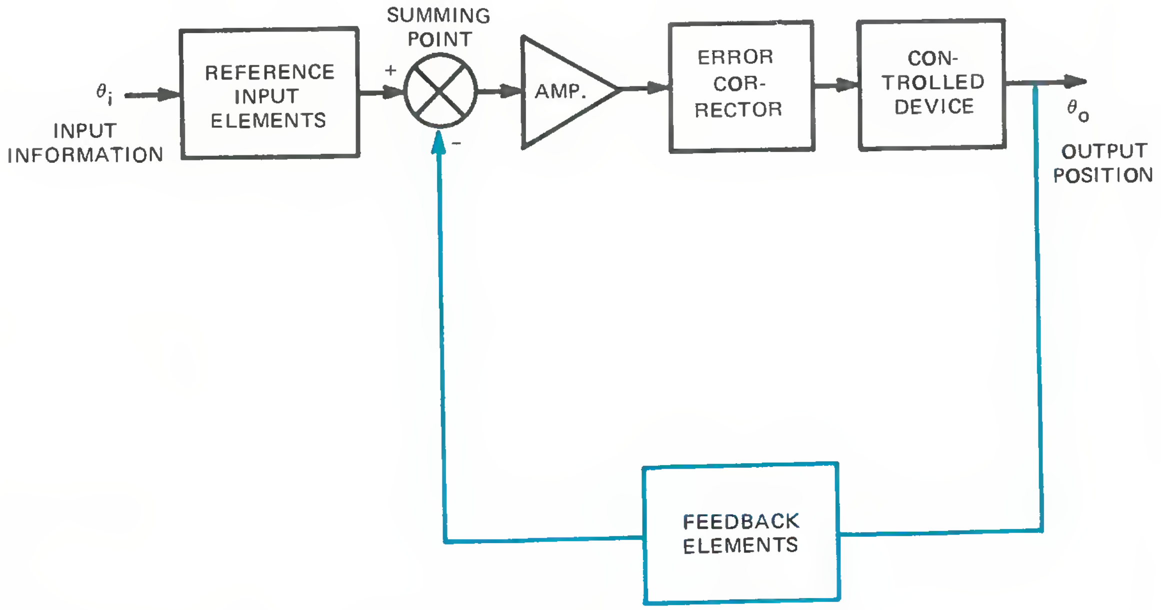


Fig. 5-3 A Generalized Servomechanism

A generalized block diagram of a servomechanism is shown in figure 5-3.

We can readily identify the components of figure 5-2 with the blocks of figure 5-3. The input information, θ_i, is the position of the TX rotor, while the TX itself is the reference input element. The control transformer, CT, is the summing point. The error corrector is the motor and the controlled device is the valve. The feedback elements consist of the gearbox and the mechanical linkage to the CT. The output information is the amount that the valve is closed or opened.

In all servomechanisms the error signal is eventually fed to an error-correcting device. This device then positions the output (valve, antenna, recorder pen, etc.) so that it corresponds to the input. In order to do this, the error corrector must be able to respond very quickly and have the ability to reverse direction. The most common device used in an error corrector is a servomotor. While AC motors are used most frequently, some applications require the use of a DC servomotor.

A DC servomotor is usually a split field motor. The field may consist of two separate windings or one center-tapped field winding which functions as two separate windings. One winding will, of course, cause motor rotation in the opposite direction compared to the other field winding. These motors may be connected in series or shunt as shown in figure 5-4.

In a servomechanism, the switch shown in figure 5-4 would be replaced by an active circuit, perhaps a transistor circuit, and the input to the field would be the amplified error signal. Its amplitude and phase, positive or negative, would determine how fast and in what direction the motor would rotate.

An AC servomotor is normally a two-phase induction motor with two field windings at right angles as shown in figure 5-5.

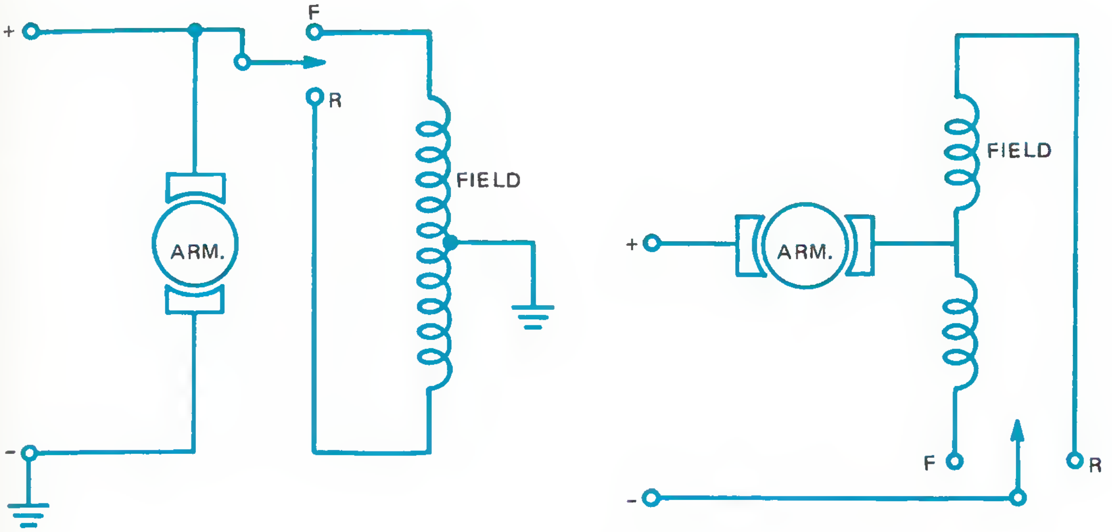


Fig. 5-4 Shunt and Series Servomotor Connection

The series capacitor, C_2, is added to the motor to insure that the excitation currents of the two windings will be 90° out of phase with each other. If the error voltage is in phase with the reference voltage, there will be clockwise rotation due to the 90° shift caused by the capacitor. If the error voltage is negative or 180° out of phase, the motor will rotate counterclockwise due to the 270° phase shift. In both cases, the direction of rotation is dependent on the polarity of the error voltage. C_1 is added to the motor to increase the impedance of the load on the error amplifier and cut down on the current drain. The value of this capacitor, which with the field winding forms a resonant circuit, is usually given in the manufacturer's specifications for the motor.

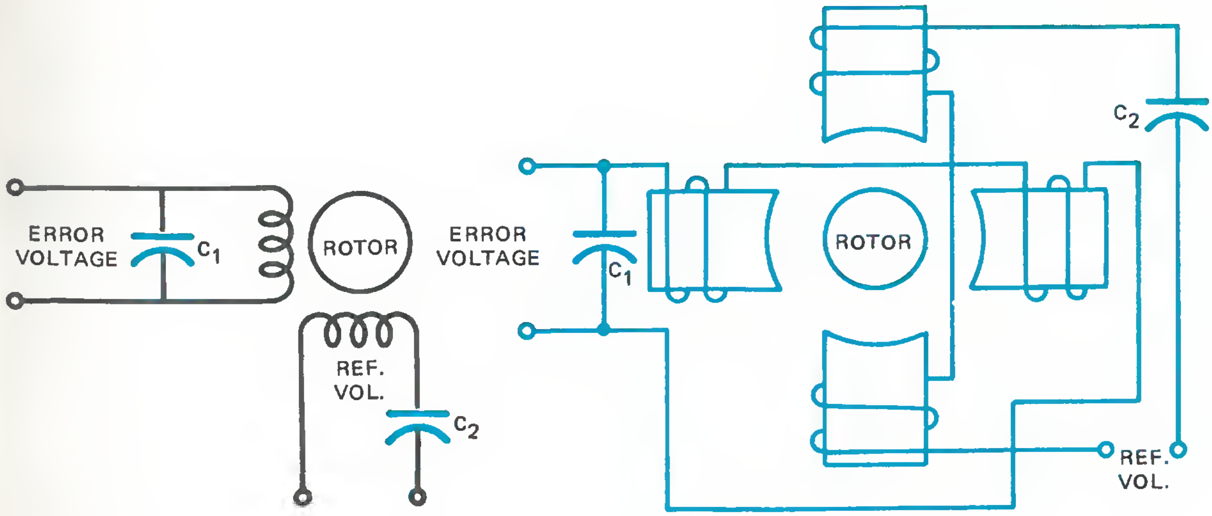


Fig. 5-5 The AC Servomotor

In an ideal system, no matter how small an input we apply to the system, we would get a change in the position of the output device. In an actual servomechanism, we cannot realize this ideal situation and must live with a situation called the *dead band*. This is defined as the range through which the input can be varied without an output response. In the case of the servomotor, if we have the rated voltage on the reference winding only, the rotor will not turn. If we slowly increase the amplitude of the voltage applied to the control winding, at some point the rotor will commence to turn. If we reverse the polarity at an equal but negative value of voltage, the rotor will begin to turn in the opposite direction. We could then plot out the curve shown in figure 5-6.

The dead band would then be $V_2 - V_1$. If we were plotting the dead band of a TX-TR combination, the horizontal and vertical axes would both be indicated as degrees, and the dead band would, of course, be measured in degrees on either side of zero.

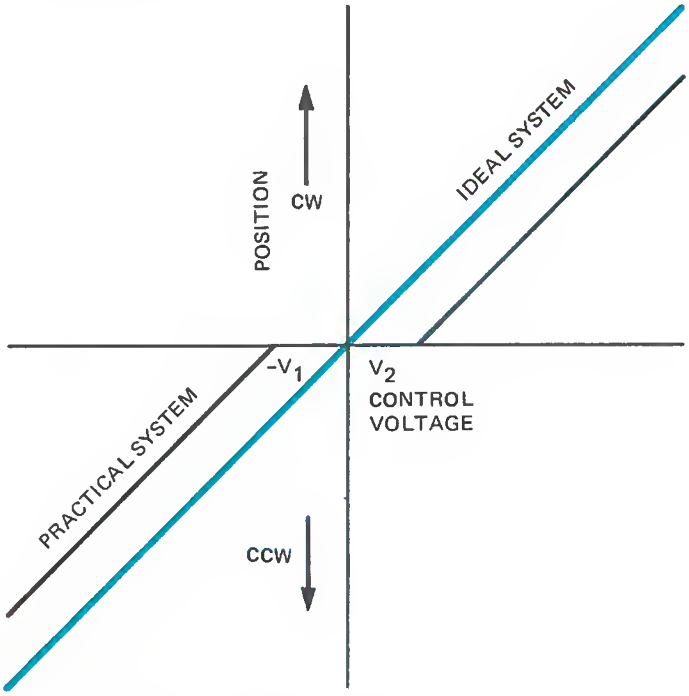


Fig. 5-6 Deadband of a Servomotor

MATERIALS

- 1 Mechanical breadboard
- 1 Servoamplifier (compatible with the servomotor)
- 1 AC servomotor 60 Hz with mount
- 1 Synchro transmitter, type 23TX6 or equivalent with mount
- 1 Synchro control transformer, type 23CDX6 or equivalent with mount
- 1 Oscilloscope
- 2 360° disk dials
- 2 Dial indices with mounts
- 1 Worm screw
- 1 Worm wheel
- 3 Spur gear 36N
- 1 Spur gear 95N
- 2 Shaft hangers (1-1/2 in.)
- 2 Shaft hangers (adjustable)
- 4 Collars
- 2 Shafts 1/4 x 4 in.
- 1 Line cord

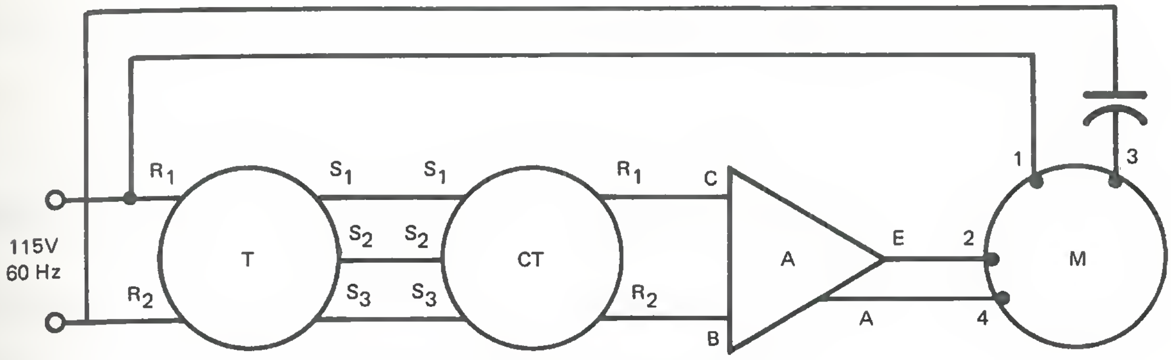


Fig. 5-7A The Experimental Setup

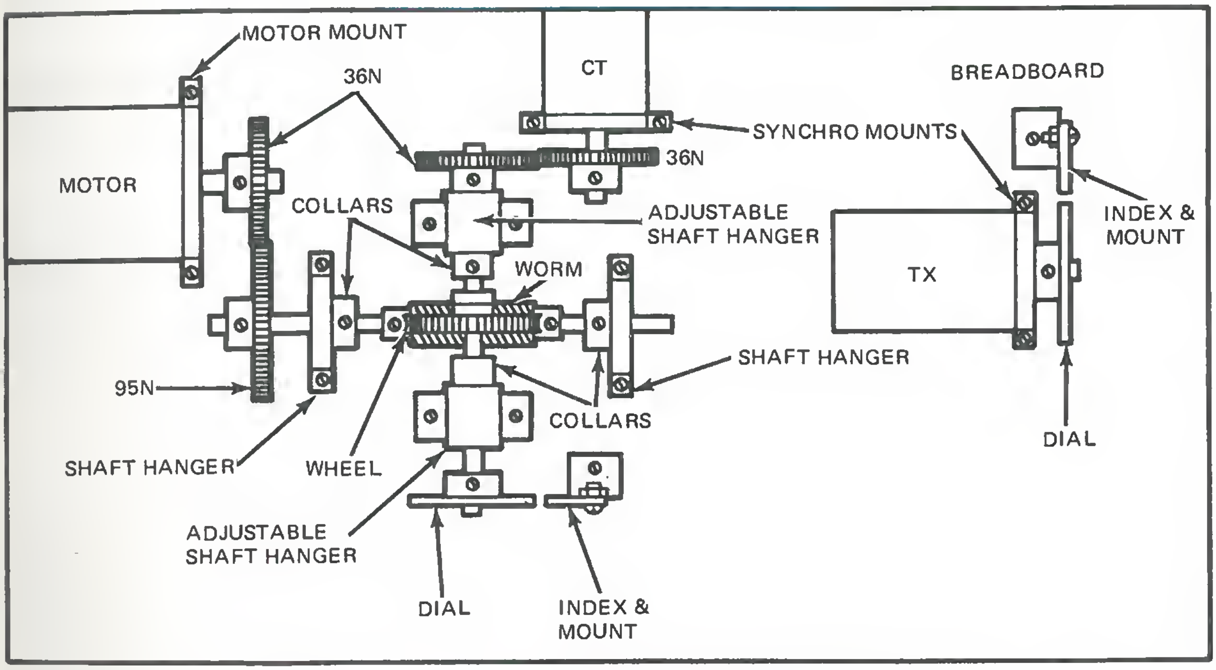


Fig. 5-7B Mechanical Assembly

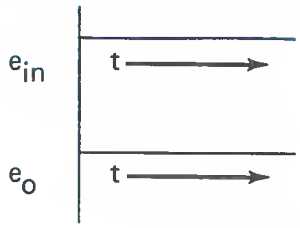
PROCEDURE

1. Assemble the system shown in figure 5-7A and B.
2. Turn the amplifier on and energize the transmitter or motor with 115V AC.
3. Set the synchro transmitter dial, θ_i, to 0° and record the displacement angle of the output dial θ_o. Note: If the output dial is unstable, lightly press the eraser end of a pencil on the motor drive gear.
4. Repeat step 3 for 360° and take your readings every 60°.
5. Reverse the input leads to the amplifier and record the output dial position for a transmitter setting of 120° and 300°.

6. Using an oscilloscope, measure the input voltage to the amplifier and also its output. Set the scope to trigger on the input to the amplifier.
7. Sketch the waveshapes of step 6 showing amplitude and phase relationships.
8. Using an oscilloscope, compare and sketch the wave shapes of the input and output of the amplifier as the input dial of the transmitter is varied. Do this for several gain settings of the amplifier. Use the input signal for sync in each case.
9. Determine the speed relationship between the motor and the control transformer rotor by counting the gear teeth.
10. Determine the speed relationship between the motor and output dial.
11. Interchange the S_1 and S_3 connections and record the effect on the direction of rotation of the output dial.
12. Do not disassemble this setup before you return it to storage as it will be used again later.
13. Plot the data taken in steps 3 and 4.

ANALYSIS GUIDE. In analyzing the results of this experiment you should speculate on what might make this system more stable. You should also explain why the output rotated in the direction it did for each of the experimental conditions. You will also want to discuss the linearity or lack of it in the curve you plotted.

θ_i	θ_o	θ_i	θ_o
0°		120°	
60°		300°	
120°			
180°			
240°			
300°			
360°			



$$\frac{N_m}{N_{CT}} = \underline{\hspace{4cm}}$$

$$\frac{N_m}{N_{Dial}} = \underline{\hspace{4cm}}$$

Fig. 5-8 The Data Table

Direction of rotation ______________	Direction of rotation ______________
$S_1 \rightarrow S_1$	$S_1 \rightarrow S_3$
$S_2 \rightarrow S_2$	$S_2 \rightarrow S_2$
$S_3 \rightarrow S_3$	$S_3 \rightarrow S_1$

Fig. 5-8 The Data Table (Cont'd)

PROBLEMS

1. What is the dead band of this system?
2. What is the gain of the amplifier?
3. What did the interchange of the stator connections do to the phase of the input to the amplifier?

experiment 6 *LOW FREQUENCY FUNCTION GENERATORS*

INTRODUCTION. Different waveshapes are often necessary in the operation or testing of servomechanisms. Devices which produce such signals are called function generators. In this experiment we will construct and examine a simple function generator.

DISCUSSION. A function generator generates an output that can be described as some mathematical function. This output may be a mechanical force or displacement, or it may be an electrical voltage or current. As an example, if y is some function of time, we can express it generally as

$$y = f(t)$$

and if this specific function of time is a cosine function, then we would have

$$y = f(t) = \cos t$$

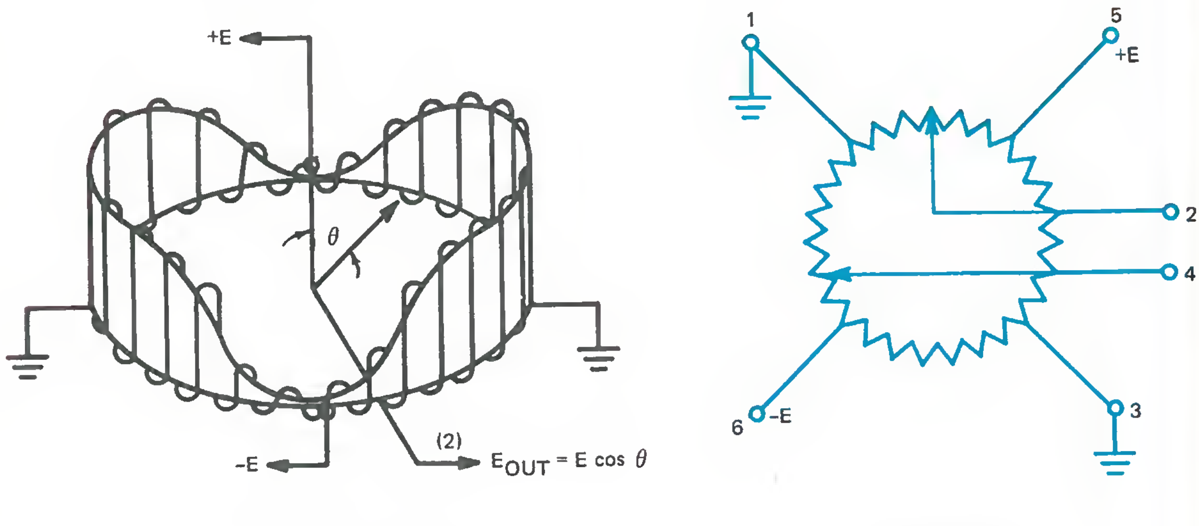
or, if the function is linear, we would write

$$y = f(t) = mt + b$$

where m is the slope of the line and b is the y value where the line crosses the y axis.

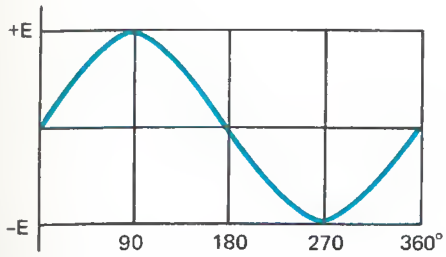
When we want a sine or square wave having a frequency above about 5 Hz, an electronic oscillator is normally used. When working with servomechanisms, much lower frequencies are often needed. Very low frequencies and special waveshapes can be generated with mechanically-driven nonlinear potentiometers.

Figure 6-1 is an example of a sine-cosine potentiometer like the one you will use in this experiment. As the slider, pin 4, moves along the top edge of the device shown in figure 6-1 (A), the voltage goes from zero to maximum positive, back to zero volts and to

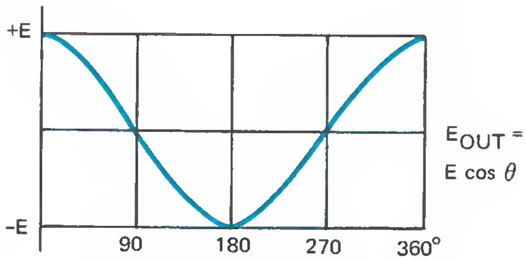


(A) CONSTRUCTION *(B) SYMBOL*

Fig. 6-1 Sine-Cosine Potentiometer



(C) OUTPUT FROM PIN 4 (SINE)



(D) OUTPUT FROM PIN 2 (COSINE)

Fig. 6-1 Sine-Cosine Potentiometer (cont'd.)

maximum negative. pin 2 is another slider placed 90° ahead of the other slider and produces the same waveshape but 90° displaced. The waves are shown as (C) and (D), respectively, of figure 6-1.

The advantage of using these types of function generators is that the potentiometers may be rotated by motors at a very low RPM, producing extremely low frequencies.

Figure 6-2 shows some other possibilities for nonlinear potentiometers.

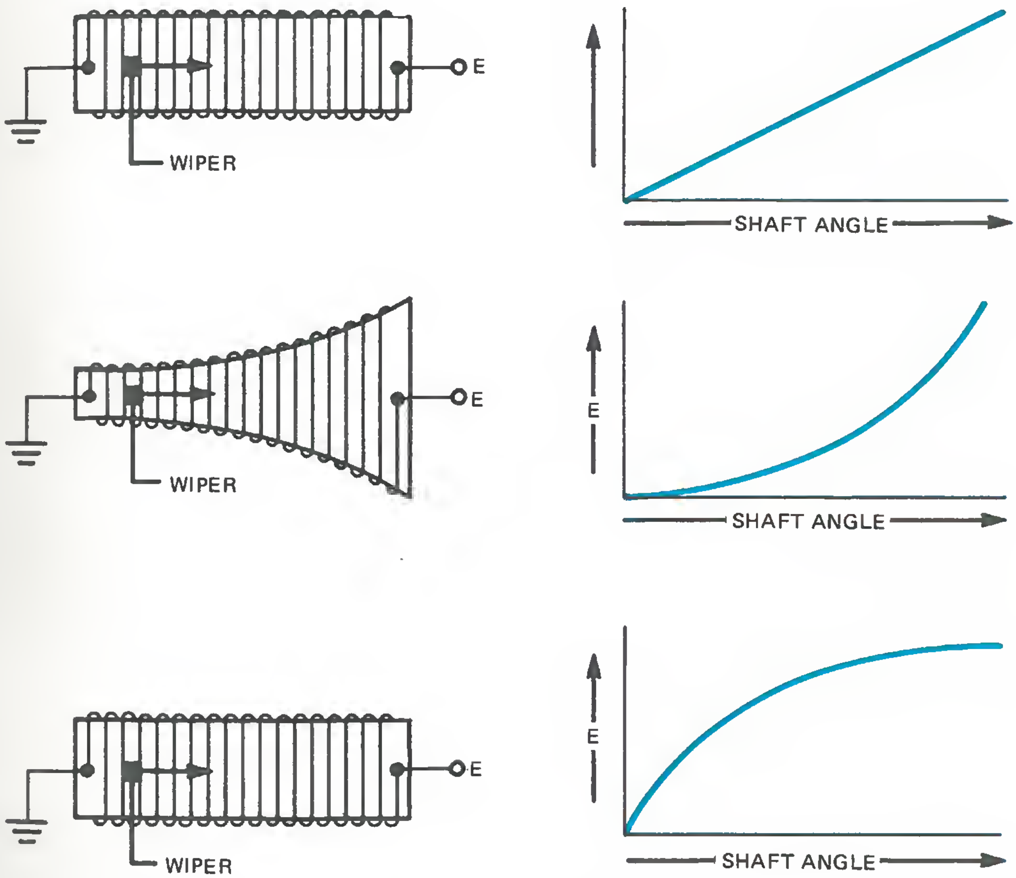


Fig. 6-2 Function Generator Potentiometers

MATERIALS

1 Breadboard with legs
1 Sine-cosine potentiometer, 10 kΩ to 20 kΩ
1 Triangular potentiometer, 10 kΩ to 20 kΩ
1 DC power supply (0–40V)
1 Potentiometer mounting bracket
1 Dial index with mount
1 360° disk dial
1 VOM or FEM
1 Motor mount
1 Oscilloscope
1 Sheet graph paper
1 DC motor, 28V
2 Spur gears 36N
2 Spur gears 95N
1 Worm wheel
1 Worm screw
2 Shaft hangers (1-1/2 in.)
2 Shafts 1/4 X 4
4 Collars
1 Harmonic drive with mount
1 Flex coupling

PROCEDURE

1. Mount the sine-cosine potentiometer on the bracket and mount the 360° disk dial on the potentiometer shaft. Mount an index for the disk dial.
2. Connect the circuit as shown in figure 6-3.

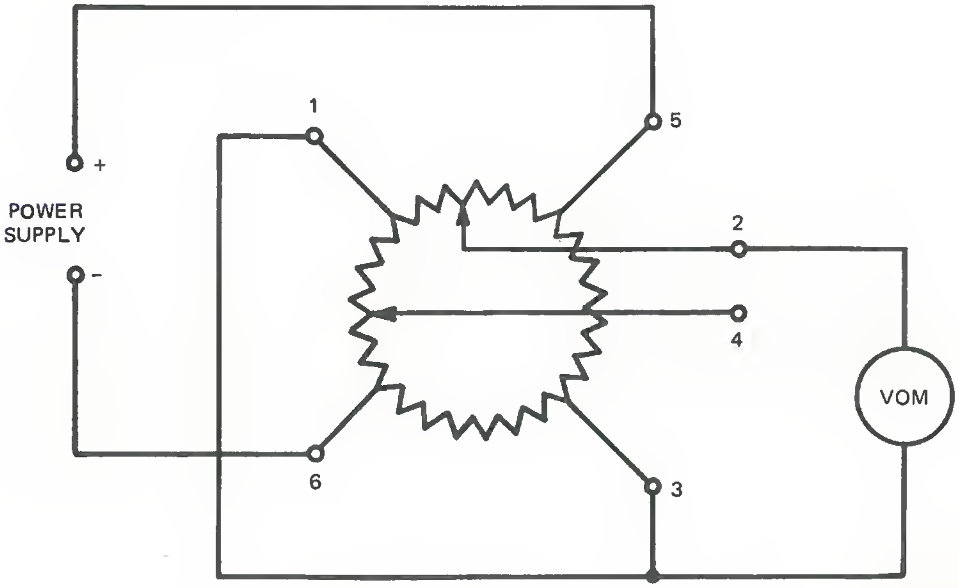


Fig. 6-3 Sine-Cosine Function Generator

3. Set the power supply voltage to 2 volts.
4. Rotate the dial a few turns and observe that the voltmeter deflects both up and down scale.
5. Zero the sine-cosine potentiometer by making the disk dial read zero for maximum up scale reading on the VOM.

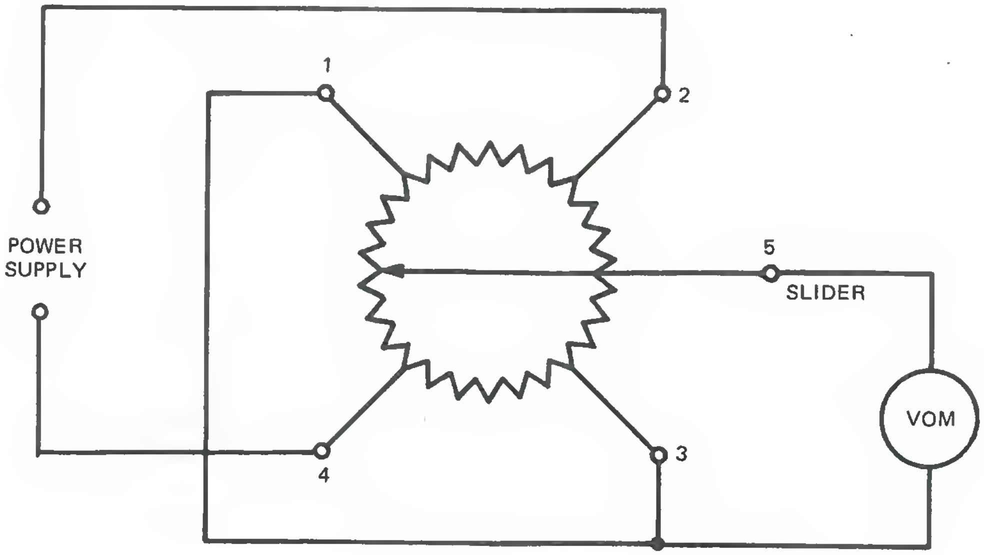


Fig. 6-4 Triangular Function Generator

6. Record the output voltage for the angles listed in the data table. You should reverse the meter leads for negative readings but remember to record those values as negative quantities in the data table.
7. Move the VOM from pin 2 to pin 4 and record the output voltage for the angles in the data table.
8. Remove the sine-cosine potentiometer from the mounting bracket and mount the triangular potentiometer.
9. Calibrate so that the dial reads zero degrees as the voltage reaches maximum positive and starts to decrease.
10. Record the data for the angles shown in the data table remembering to indicate the proper sign.
11. Plot the outputs of the sine-cosine potentiometer and the triangular potentiometer on graph paper.
12. Assemble the low-frequency function generator shown in figure 6-5.
13. Mount the sine-cosine potentiometer on the low frequency function generator. Connect the circuit as shown in figure 6-3 but use an oscilloscope in place of the VOM.
14. Record the output at maximum frequency.
15. Record the output at pin 4.
16. Remove the sine-cosine potentiometer and replace it with the triangular potentiometer. Connect the circuit as shown in figure 6-4 but with an oscilloscope instead of a VOM.
17. Record the output waveform at maximum frequency.

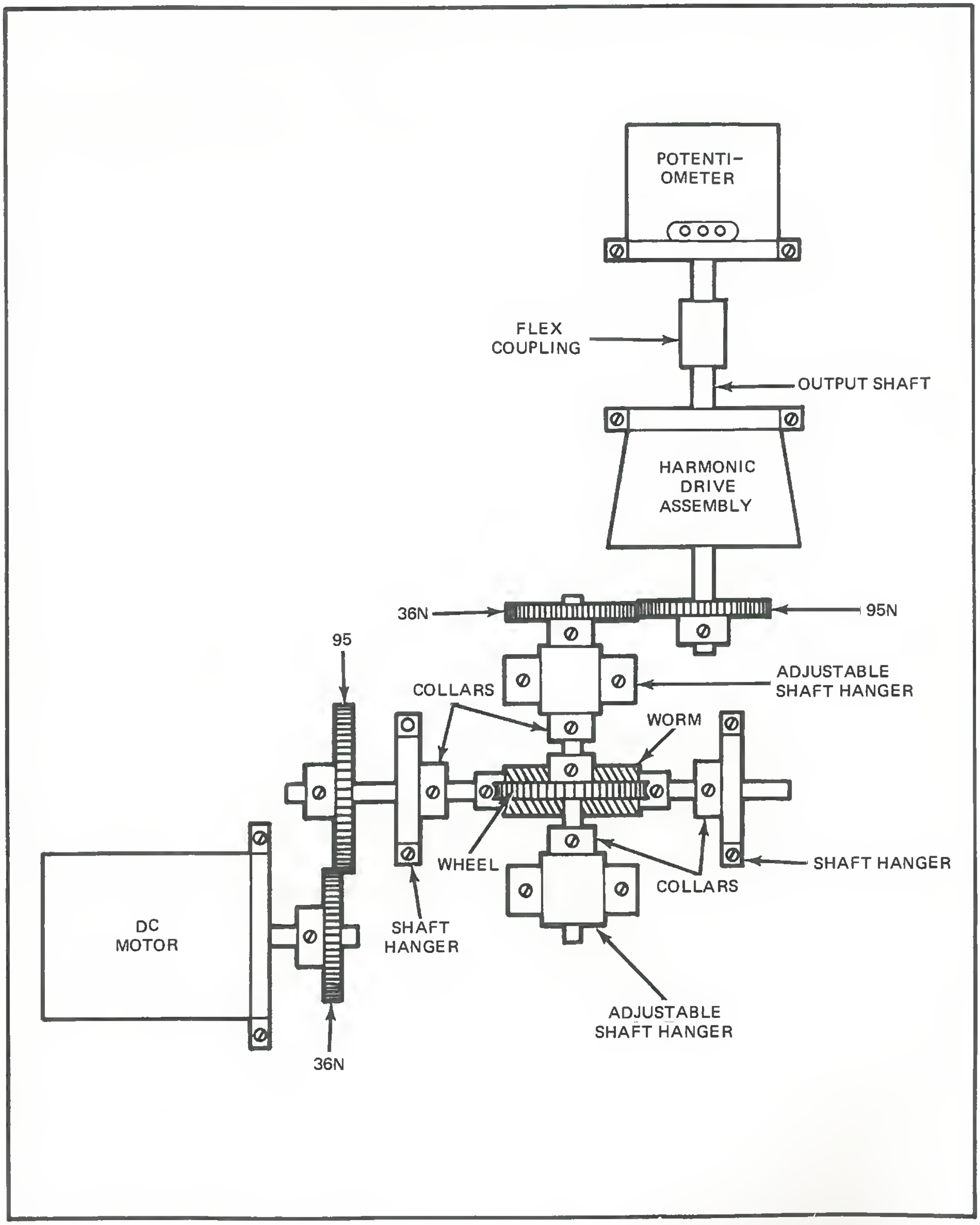


Fig. 6-5 The Experimental Function Generator

ANALYSIS GUIDE. Compare your results using the VOM and the oscilloscope.

Angle θ (degrees)	Sin-Cos Pot.		Triangular Potentiometer
	pin 2	pin 4	
0			
20			
40			
60			
80			
90			
100			
120			
140			
160			
180			
200			
220			
240			
260			
270			
280			
300			
320			
340			
360			

Fig. 6-6 The Data Table

Output	
pin 2	+ 0 –
pin 4	+ 0 –
triangular	+ 0 –

Fig. 6-6 The Data Table (Cont'd)

PROBLEMS

1. What is the phase relationship between the sine and cosine functions?
2. Write the mathematical equation for the output at pin 2 of the sine-cosine potentiometer. Define each symbol you use.
3. Write the equation for the output of pin 4 of the sine-cosine potentiometer and explain the symbols.
4. Write the equation for the output of the triangular potentiometer over the interval of 0 to π.
5. Write the equation for the output of the triangular potentiometer over the interval π to 2π.

experiment 7 STABILITY CONTROL

INTRODUCTION. In this experiment we will investigate one of the most serious problems encountered in servomechanisms, that of holding the output at a position corresponding to the input.

DISCUSSION. With an ideal servomechanism the output should exactly follow the input. Further, it should do this instantaneously; that is, with no time lag between input change and output correction. It is, of course, virtually impossible to achieve these conditions in a practical situation. We can come very close to the ideal situation if our system will respond to very small errors, has high sensitivity, responds very quickly to input changes, and does not overshoot or hunt. In satisfying the first two conditions we often introduce instability or overshoot and hunting into the system.

If we suddenly change the input of a servomechanism from some steady state position to a new position, the output will attempt to follow this change. How close and fast it is able to do this is a function of the various components that make up the system.

In a servo system the moving force is supplied by the electromotive torque of the servo motor. The acceleration and motion in the system is supplied by this motor. If the system is linear, the error signal is proportional to the difference between the actual load position and the input shaft position. The relationship existing between the load position, θ_o, and the motor torque, T_m, is described by the equation

$$\boxed{T_m = C(\theta_i - \theta_o)} \qquad (7.1)$$

where θ_i is the input position that the load is attempting to achieve and C is a constant of the system given in torque per unit of load displacement.

As we examine figure 7-1 we will notice that the output can produce at least two distinct motions.

In part (A) of figure 7-1 the system overcorrects in one direction and then overcorrects to a lesser degree in the reverse direction. Eventually the system corrects the proper amount and it settles down in the neighborhood of θ_2'. This type of response is called overshoot.

The other type of response, shown in figure 7-1(B), is called hunting. This type of response is caused by a system that has essentially no damping or frictional load on the correcting device. It overcorrects on the first pass and then, because there is no friction, it overcorrects an equal amount in the reverse direction. It will repeat this indefinitely unless an external force is applied to the system to damp it.

We can cut down on both overshoot and hunting if we load the system or use some damping. The output response to a step function input for various degrees of damping is shown in figure 7-2.

In an overdamped system the output eventually reaches the desired position but the time lag is excessive and is therefore an undesirable situation. The underdamped sys-

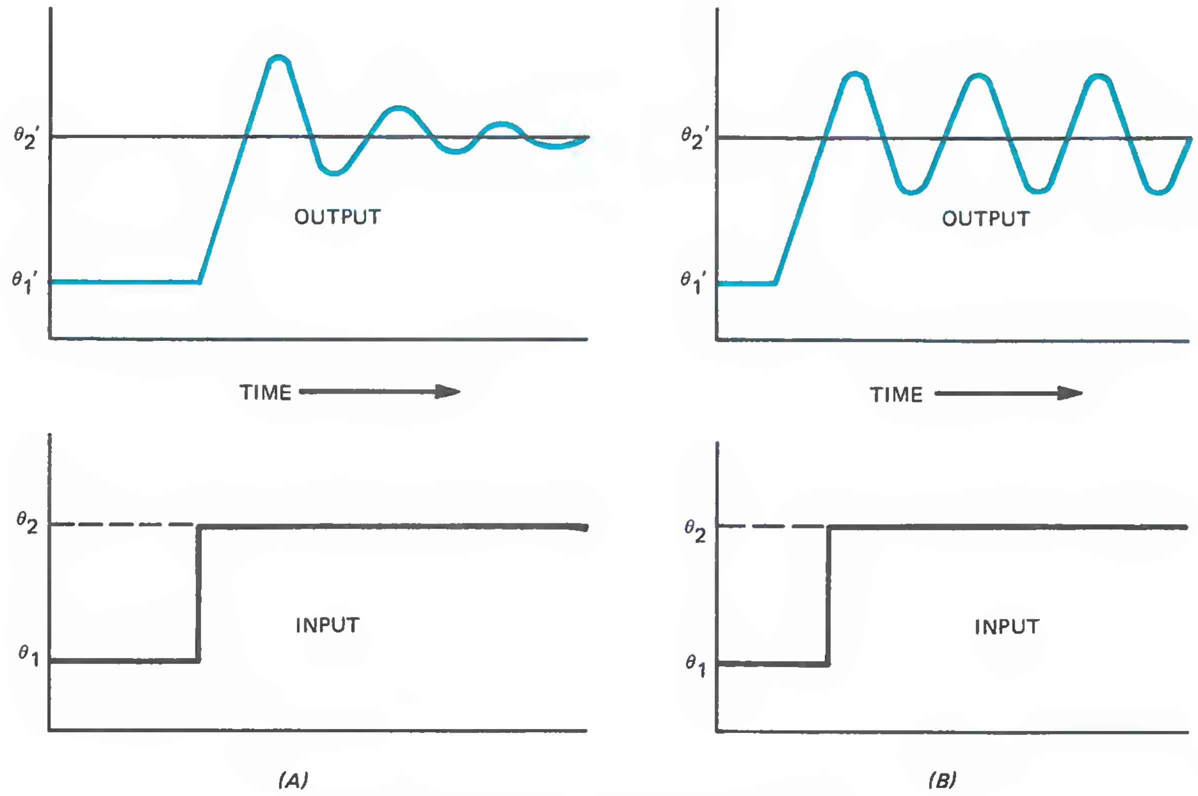


Fig. 7-1 Hunting and Overshoot in a Servo

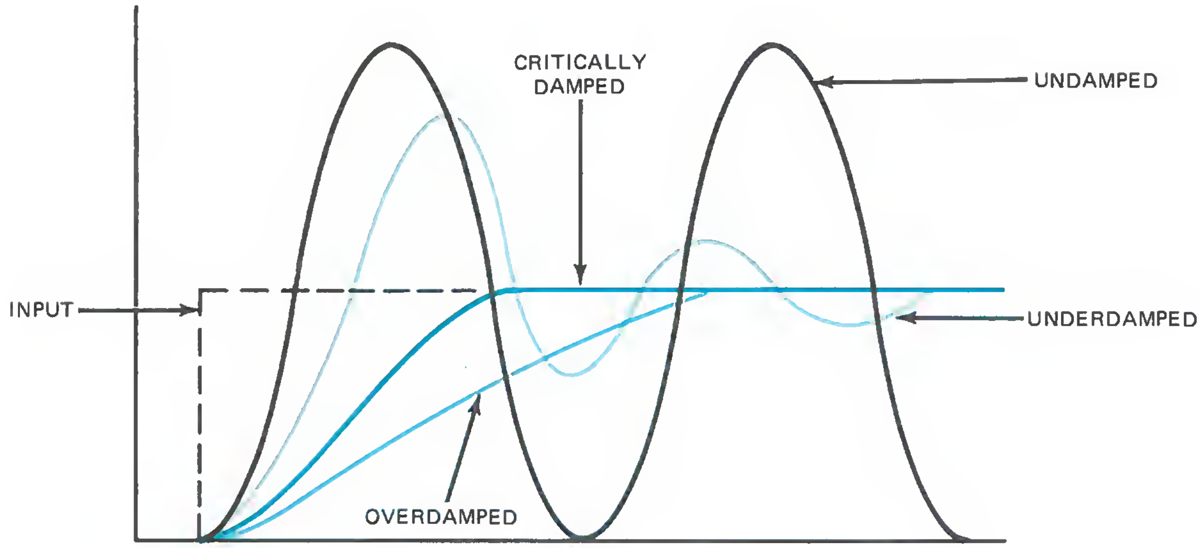


Fig. 7-2 Servo Output for Various Damping Factors

tem is also undesirable. Even though it reaches the output position rather quickly, it has an excessive amount of overshoot. The best situation is a critically damped system which reaches a stable position with minimum time lag and no overshoot.

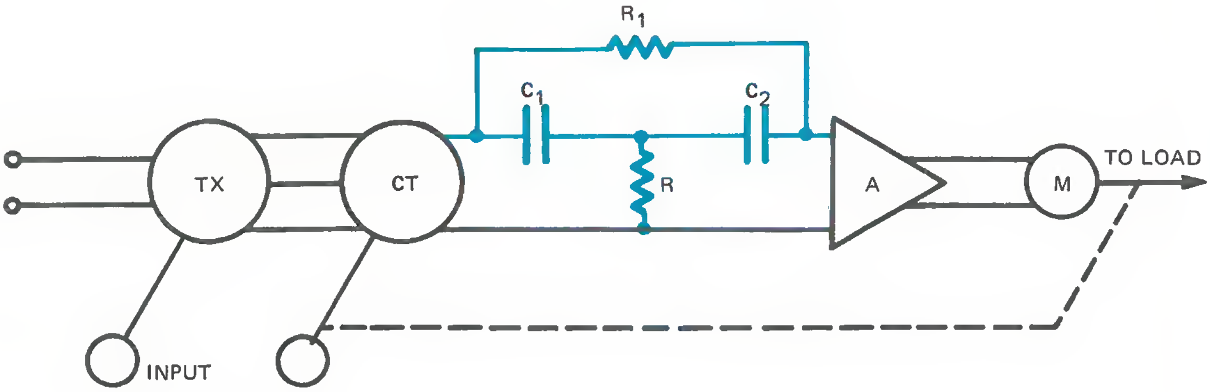


Fig. 7-3 Bridged-T Error Control

One can add the required damping by a mechanical means such as a paddle wheel turning in an oil-filled container. A more common means is to add the damping via appropriate electrical circuits in the servo system. Consider the circuit shown in figure 7-3. Before we can ascertain how this network will cut down on oscillations and errors in the system, there are some terms that must be defined. The *motion frequency* (f_m) is the one at which the load tends to oscillate. It is normally quite low, say 10 Hz or less.

The *error signal* or power frequency (f_o) is the same as the power frequency that is driving the synchro transmitter. The error signal is caused by the difference in the load and input positions. The motion frequency will tend to modulate the power frequency so that one will get upper and lower sidebands into the amplifier. Let us look at the frequency response and phase shift curve of the bridged-T circuit to see how this circuit will aid in combating the instability problem.

Notice that at the power frequency, f_o, there is an amplitude dip and zero phase shift.

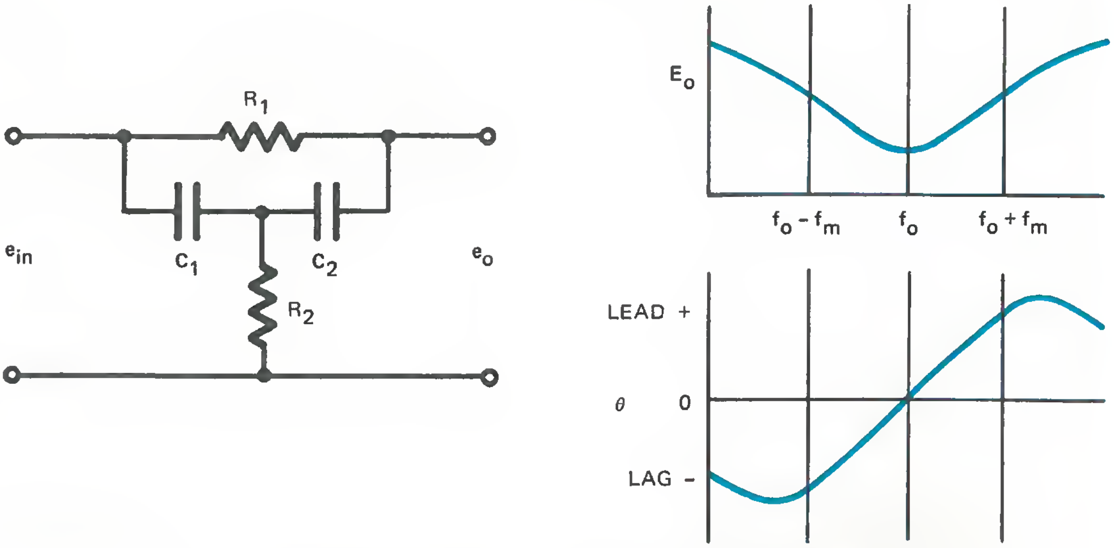


Fig. 7-4 Response of the Bridged T

At the upper sideband, $f_o + f_m$, there is an amplitude rise and a phase lead, while at the lower sideband the signal is lagging. The phase lead signal will compensate for the time lag caused by the oscillations of the load. The circuit center frequency is given by

$$\boxed{f_o = \frac{1}{2\pi C\sqrt{R_1 R_2}}}$$

The values of resistance and capacitance should be chosen so that the center frequency of the circuit corresponds to the power frequency, f_o. The two capacitors normally are chosen to have the same value. The slope of the phase curve is given by the time constant of the circuit, R_1C_2. As can be seen from the response curve, when the input is charging rapidly as when its position is suddenly changed, the error will be great and the bridged-T circuit will allow the output to adjust more rapidly. As the error decreases, the sidebands are closer to the power frequency and the input to the amplifier is attenuated.

MATERIALS

- 1 Mechanical breadboard
- 1 Servoamplifier (compatible with the motor)
- 1 AC servomotor 60 Hz with mount
- 1 Synchro transmitter, type 23TX6 or equivalent with mount
- 1 Synchro control transformer, type 23CT6 or equivalent with mount
- 1 Audio generator
- 1 Oscilloscope
- 2 Resistance decade boxes
- 2 Capacitance decade boxes
- 1 Strobe light
- 1 Capacitor 0.01 µF, 150W VDC
- 1 Worm wheel
- 1 Worm screw
- 3 Spur gear 36N
- 1 Spur gear 95N
- 2 Shaft hangers (1-1/2 in.)
- 2 Shaft hangers (adjustable)
- 4 Collars
- 2 360° disk dials
- 2 Dial indices with mounts
- 2 Shafts 1/4 x 4 in.
- 2 Sheets of 3-cycle semilog graph paper
- 1 Line cord

PROCEDURE

1. Assemble the system shown in figure 7-5.
2. Determine the electrical zero of both the transmitter and the control transformer
3. Adjust the shaft dials so that the mechanical zero corresponds to the electrical one found in step 2.
4. Energize the system and suddenly rotate the input to 70°. (This should cause the output to become unstable and oscillate.)
5. Using a strobe light, determine the frequency, f_m, of the load oscillation.
6. With the load still oscillating, use an oscilloscope to record the output of the amplifier. Be sure to record the period of the wave.
7. Insert the bridged-T network between the control transformer and the amplifier. Let $C_1 = C_2 = 0.1\ \mu F$, $R_1 = 7\ k\Omega$ and $R_2 = 100\ k\Omega$.

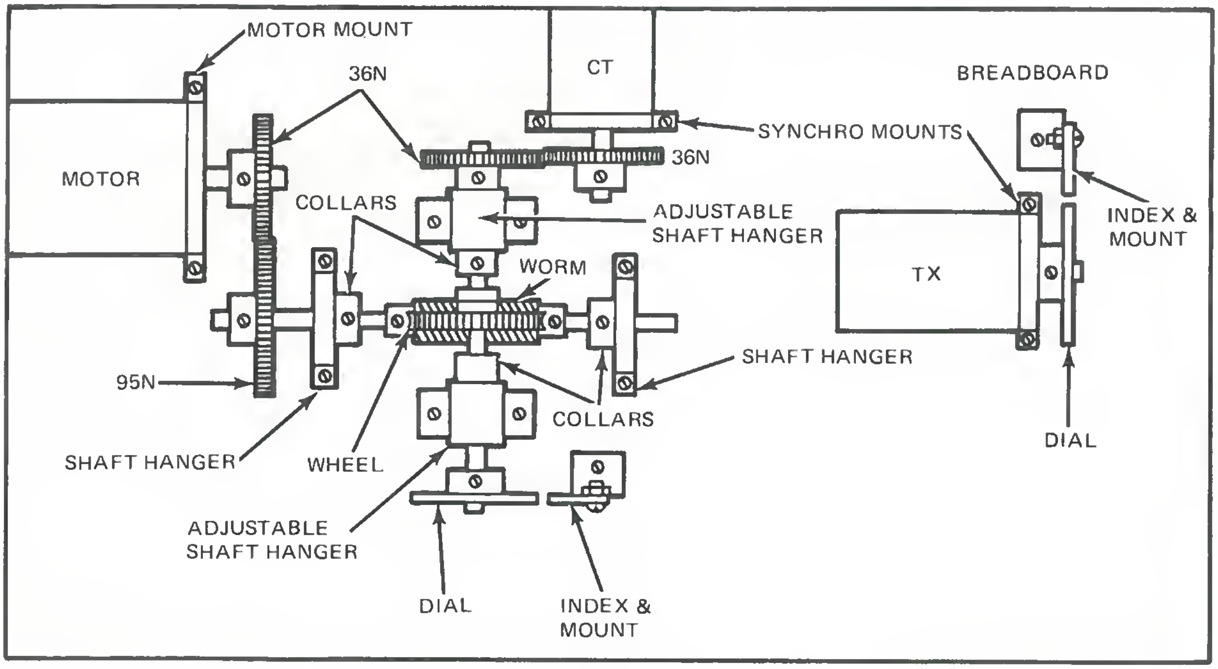


Fig. 7-5 Mechanical Assembly

8. Set the input to several different settings and record the effect of the T network on the stability of the system.
9. Repeat step 8 for several different values of resistance and capacitance.
10. In each case observe the amplifier output on an oscilloscope as the input is changed.
11. Using an audio generator, take data on just the bridged-T network to plot a response curve (output versus frequency) on 3-cycle semilog graph paper. Use the values of step 8.
12. Using an oscilloscope, determine the phase angle at each of the data points of step 11.
13. Plot the data of step 11 on an 8-1/2 by 11" sheet of 3-cycle semilog graph paper.

ANALYSIS GUIDE. In analyzing the data from this experiment you should discuss what effect a less powerful servo motor would have on the oscillating tendency of the system. Some discussion of how mechanical damping could be supplied to the system should also be included in your discussion.

PROBLEMS

1. What would be the relative output of the bridged T at the motion frequency, f_m, determined in step 5 as compared to the output at 60 Hz plus f_m?
2. Would the bridged T have a leading or lagging phase angle at 60 Hz + f_m?
3. What would be the effect of adding a network that introduces a lagging phase angle?

experiment 8 *MAGNETIC AND ELECTROMAGNETIC AMPLIFIERS*

INTRODUCTION. Amplification can be accomplished through electromechanical or magnetic means as well as with electronic amplifiers. In this experiment we will examine some of these basic types of nonelectronic amplifiers.

DISCUSSION. Before entering into a discussion of magnetic and electromagnetic amplifiers, let's review the concept of amplification. Amplification or gain, A, of a voltage amplifier is

$$A_v = \frac{\Delta E_{out}}{\Delta E_{in}}$$

where ΔE_{out} is the change in output voltage and ΔE_{in} is the change in input voltage. As an example, if the output voltage changes from 50 volts to 100 volts while the input changed from one volt to six volts, the gain

$$A_v = \frac{100 - 50}{6 - 1} = 10$$

What we are saying is that a small change in input, 5 volts, caused a larger change, 50 volts, at the output. We use a small voltage to control a large voltage.

The same is true for power. If the output power changes from 0 to 100 watts while the input changes from 0 to 1 watt, the power gain, A_p, would be 100. It is important to note that here we did not specify that the power was dissipated from an alternating-current or direct-current source. It would not matter. In fact, the input of one watt could be DC and the 100 watt output AC, or vice versa. The fact remains, in either case, that you are *using* one watt *to control* 100 watts.

Magnetic amplifiers utilize the concept of magnetic saturation. The heart of the magnetic amplifier is the saturable core reactor. When a saturable reactor is used in a circuit to amplify, the entire circuit becomes a magnetic amplifier.

Recall from circuit theory that the inductance, L, of a coil is related to flux and current by

$$L = N\frac{d\theta}{di}$$

where N is the number of turns, θ is the flux and i is the current. Considering N to be a constant for a particular device, inductance is proportional to how much the flux changes for a unit change in current $\frac{d\theta}{di}$. That is to say, the more the magnetic flux changes for a unit change in current, the greater the inductance. Inductance is directly proportional to

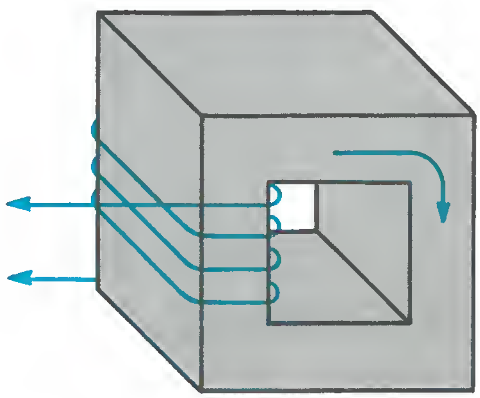


Fig. 8-1 Inductor

opposition (inductive reactance, X_L) so the greater the $\frac{d\theta}{di}$, the greater the opposition. The inductor of figure 8-1 will have an inductance, L, dependent upon the magnetic properties of the core:

$$L \propto \mu N^2 A$$

where μ is the magnetic permeability, N is the number of turns and A is the cross-sectional area of the core. This, then, tells us that if we can vary the effective area of the core, we can vary the opposition. This area could be varied physically or magnetically. If a magnetic field is externally induced into the core, there is less core left for magnetic flux; thus, the effective area is reduced. The idea of varying the effective area by magnetic means is shown in figure 8-2.

As the resistance, R, is decreased, the current, I_{DC}, increases, creating more flux in the core. This process can continue until the core is saturated, at which time there is no iron core left for the flux produced by the current from the AC source, I_{AC}. This means that the inductor is now essentially an air core coil with much less inductance and, consequently, less reactance than before. With less opposition, a higher current, I_{AC}, results. The DC supply is used to control the alternating current source. By having many many turns on the DC winding, saturation can be accomplished with relatively small currents (θ = NI).

You should realize that if the core is just barely saturated, the opposition to the alternating current will be different during one half cycle than it is during the other. This is true because one half of the cycle will tend to bring the core out of saturation when the flux is in the opposite direction of the existing flux and drive it further into saturation when the flux directions are the same.

Recall that on the basic saturable reactor of figure 8-2 there are many more turns on the control side than on the alternating current (controlled) side. This is, in effect, a step-up relationship so that a very high AC voltage could result in the control winding. The solution to this problem is to arrange the windings so that the AC component cancels in the control winding, but the control winding can still saturate the core. A possible arrangement is shown in figure 8-3.

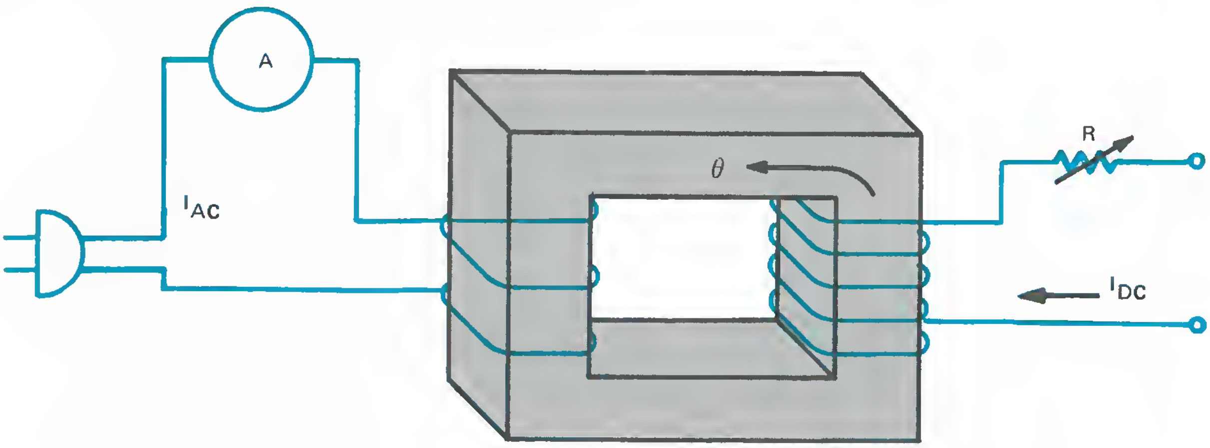


Fig. 8-2 Core Saturation

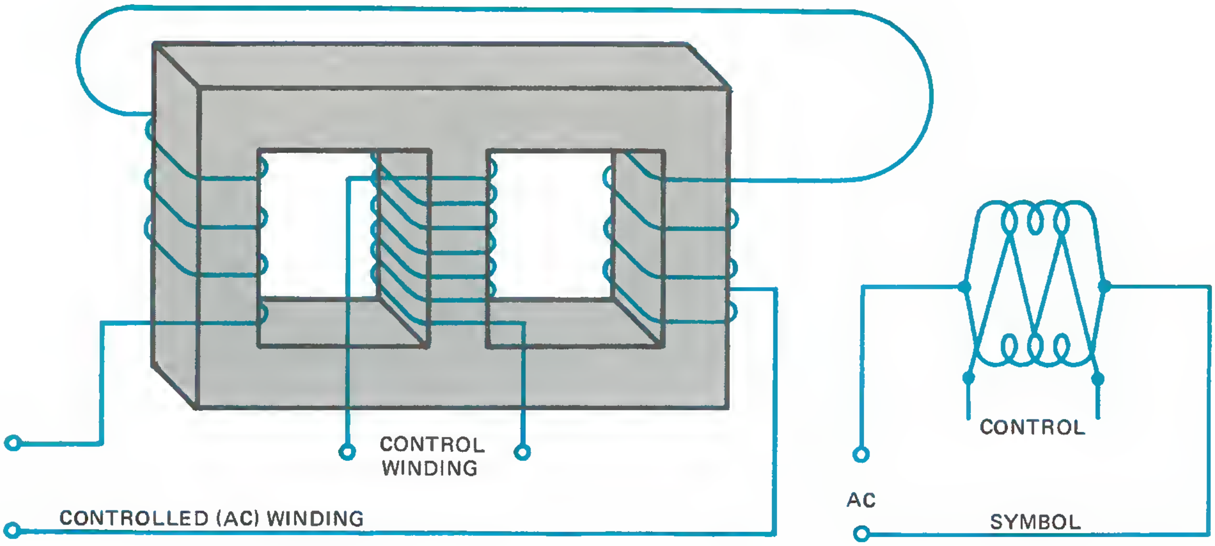


Fig. 8-3 Saturable Reactor and Symbol

The flux path for the control winding is through both sides of the core (parallel paths) tending to saturate it. The AC windings are opposite so that on any given half cycle the AC flux through the center leg cancels out.

Figure 8-4 shows a practical magnetic amplifier. The diodes prevent current in the direction that would tend to bring the core out of saturation. In this way, the AC current always drives toward saturation.

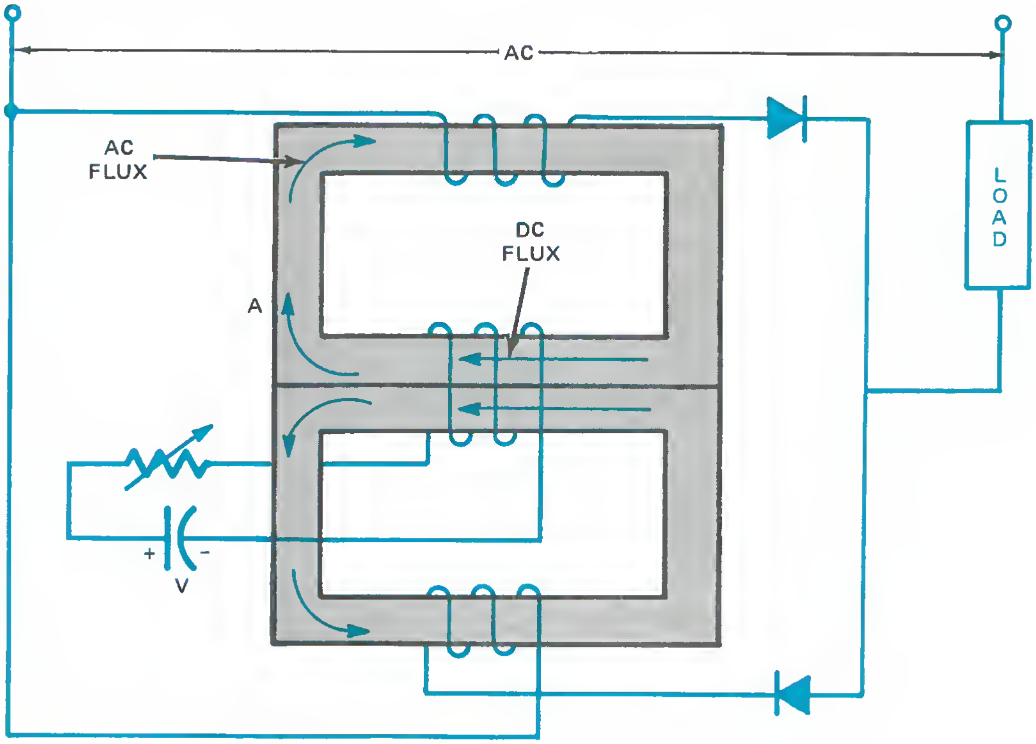


Fig. 8-4 Magnetic Amplifier

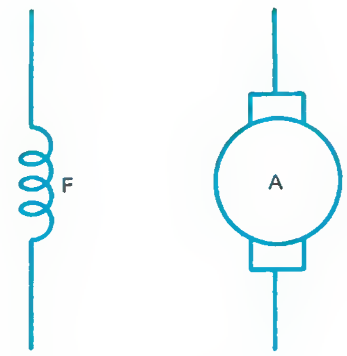


Fig. 8-5 DC Generator

Another winding can be added to the center leg to determine the amount of flux before the control (or error) signal is applied. This establishes the operating point and is called the bias winding.

An *electromagnetic* amplifier is essentially a DC generator driven by a constant speed motor. These are often built on the same shaft and in the same housing but can also be separate parts.

A DC generator is made up of a field and an armature as represented schematically in figure 8-5. The field winding creates the magnetic field inside the generator whenever a current is supplied to the windings. The armature is turned in the field, generating an output voltage. In order to use the generator as an amplifier, the error signal or whatever signal is to be amplified is fed to the field with the armature output being the amplified signal.

Figure 8-6 shows the arrangement for using the electromechanical device as an amplifier. The AC motor is turning the generator armature and, when there is no input to the field winding (no error), there is no magnetic field so no output from the armature is produced. As the error increases the field current,

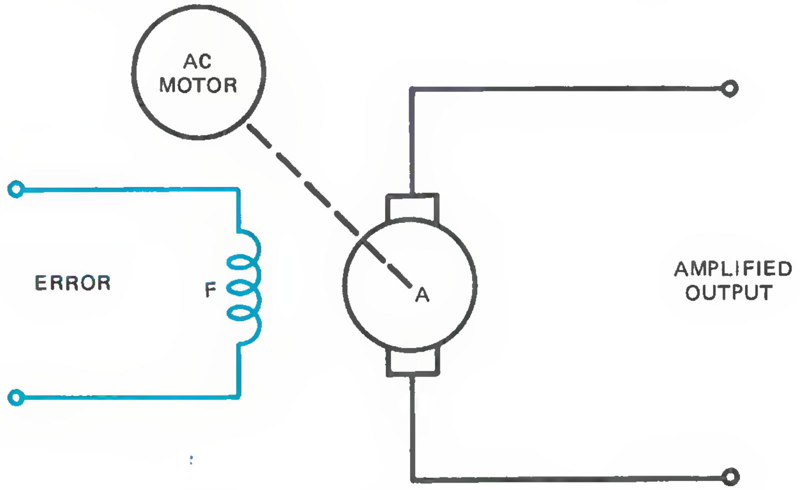


Fig. 8-6 Electromagnetic Amplifier

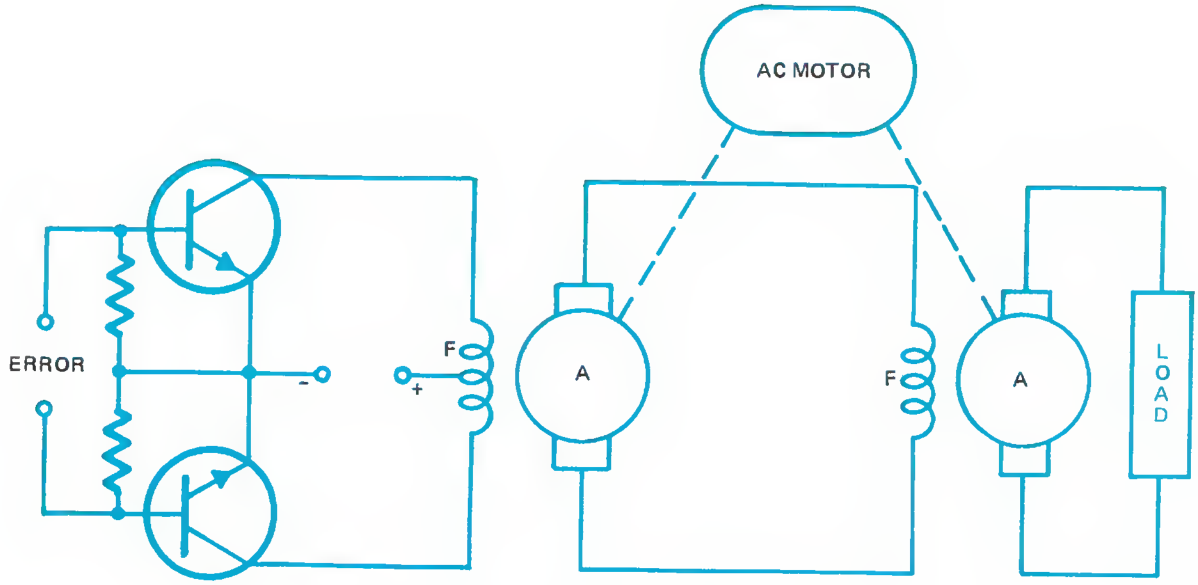


Fig. 8-7 Three-Stage Servoamplifier

and thus the magnetic field, the output increases. The power at the output can be many hundreds of times the magnitude of the input power; thus the generator is serving as an amplifier. When large gains are necessary, the output of the electromagnetic amplifier can feed another (larger) generator field to be amplified still more. Also, electronic amplifiers can precede the first generator. Figure 8-7 shows such a system.

MATERIALS

- 1 Motor generator (or separate units that can can be connected together). Generator field windings must be accessible
- 1 Saturable reactor (magnetic amplifier)
- 1 DC power supply (0 - 40V)
- 2 Resistors, 10Ω, 10W
- 1 Lamp (wattage selected so as not to damage the saturable reactor chosen)
- 1 VOM or FEM
- 1 Oscilloscope
- 1 AC current meter (0 - 5A)

PROCEDURE

1. Connect the circuit shown in figure 8-8. If there is a bias winding on your reactor, leave its terminals open.
2. Increase the control (DC) current until the lamp has a low red glow.
3. Complete the first line of the Data Table, figure 8-9.
4. Increase the control until the lamp is about 60 to 70% of full brightness. Complete line two of the Data Table.

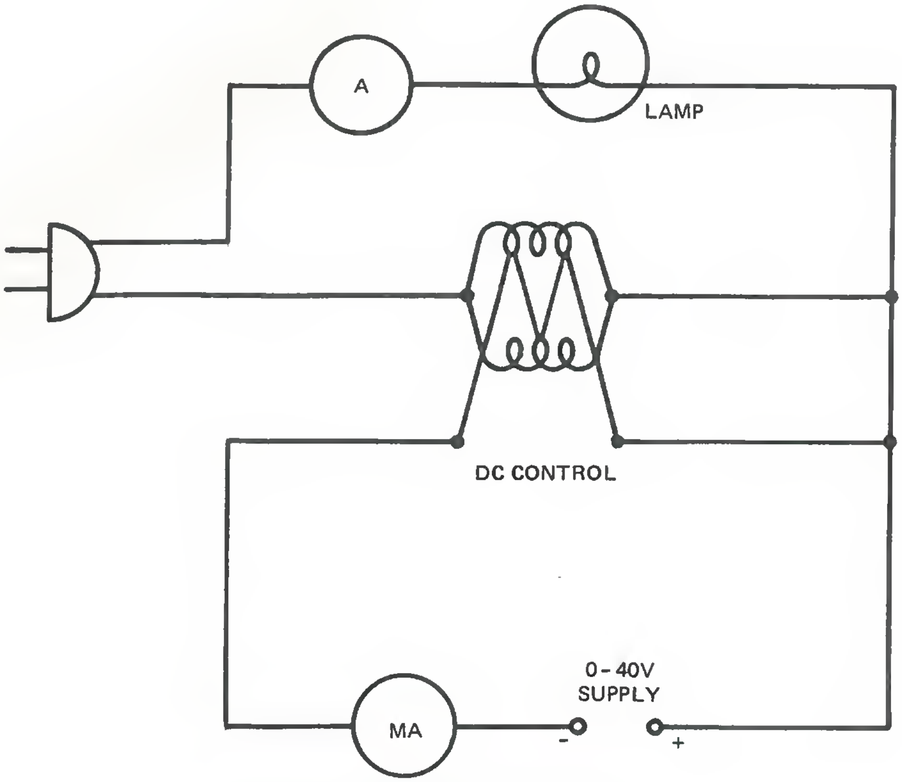


Fig. 8-8 Magnetic Amplifier

5. Increase the control current until full brightness is just barely achieved. Complete the Data Table for the magnetic amplifier.

6. If your reactor has a bias winding, connect it to a DC supply and increase the current until the lamp begins to glow. Observe the effect on the control current by rerunning part of the previous experiment. Summarize the results.

7. Reverse the polarity of the DC control and experiment around. Does it have any effect without the bias, with the bias, or when the bias is also reversed? Summarize the results.

8. Connect the circuit of figure 8-10. If separate units are used, mechanically connect the AC motor to the DC generator.

9. Measure and record the output current and voltage (armature) with the field disconnected. Record the data observed.

10. Apply power to the field and increase until the *output* current is 0.5A and complete line two of the Data Table for the electromagnetic amplifier.

11. Repeat step 10 for output currents of 1.0 and 1.5 amps and record in the Data Table. Reduce these current values if they are beyond the capability of your motor or generator.

12. Reverse the polarity of the field and observe the results. Summarize the results in the Data Table.

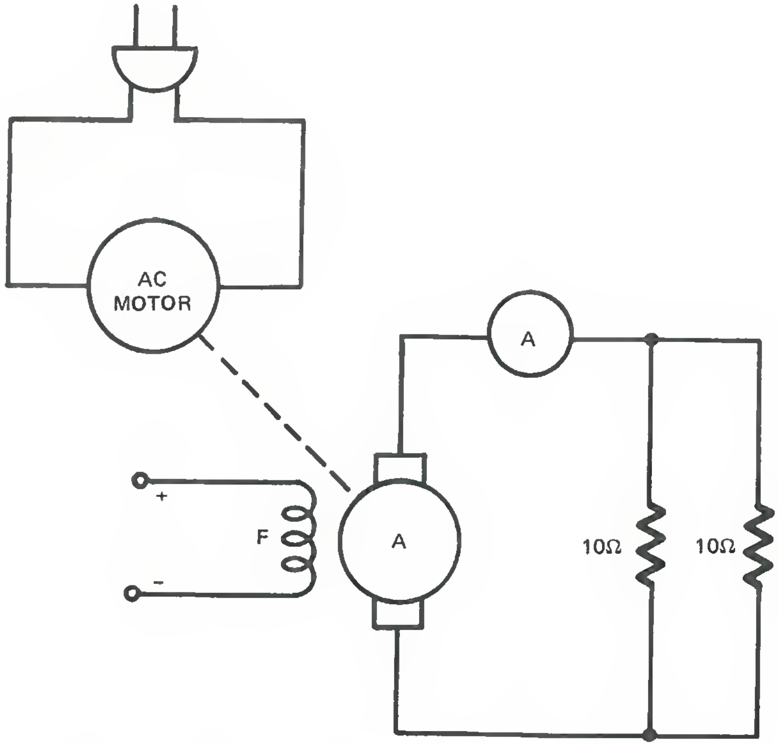


Fig. 8-9 Electromechanical Amplifier

	Control (DC)			Controlled (AC Load)				
	Current	Voltage	Power	Current	Voltage	Power	Waveform	Power Gain
1								
2								
3								

Results of Step 6:
Results of Step 7:

Fig. 8-10 Data Tables

Results of step 12:

Control (Field)				Controlled (Armature)			Results
	Voltage	Current	Power	Voltage	Current	Power	Power Gain
1					0.5 A		
2					1.0 A		
3					1.5 A		
4							

Fig. 8-10 The Data Tables (Cont'd)

ANALYSIS GUIDE. Explain the reasons for the results and difference in results of reversing the polarities of the inputs of the two devices studied. Explain the reasons for the waveforms of the magnetic amplifier output.

PROBLEMS

1. Draw a magnetic amplifier circuit similar to the one you used in this experiment but use two diodes to prevent the core from being driven *out* of saturation by the AC current.
2. Explain the results you would obtain if you got both diodes in reverse of what they were intended.
3. What probable waveform would you expect across the load of problem one for (a) low control currents and (b) high control currents?
4. With large magnetic amplifiers, several seconds or maybe even a minute of time delay is observed. Use the definition of inductance and explain why so much time is required for the load current to flow after the DC voltage has been applied.
5. Draw a closed loop servomechanism using a follow-up potentiometer type of operation and use one electronic and one electromechanical amplifier to drive a DC motor load positioner.

experiment 9 CLOSED LOOP SERVOMECHANISMS

INTRODUCTION. Closed loop servomechanisms come in many varieties. In this experiment we will investigate one which involves electromechanical amplification and a follow-up potentiometer for feedback.

DISCUSSION. A closed loop servomechanism is characterized by a feedback loop so that the results of the controller (load condition) can be compared with the command (reference) input. If there is disagreement between the two, an error is produced which is used to correct the difference. A generalized block diagram of a servomechanism is shown in figure 9-1.

The input to the system is mechanical and consists of degrees of clockwise or counterclockwise rotation of the control potentiometer shaft. The output is also mechanical. The feedback is accomplished through a mechanical coupling to the feedback potentiometer. As the feedback potentiometer approaches the same position as the command potentiometer, the input to the summing amplifier approaches zero and the motor shuts off. The system has reached a null position. When the input shaft is changed the output changes because of the error produced, and again the null position is achieved causing the load to be positioned according to the input potentiometer setting.

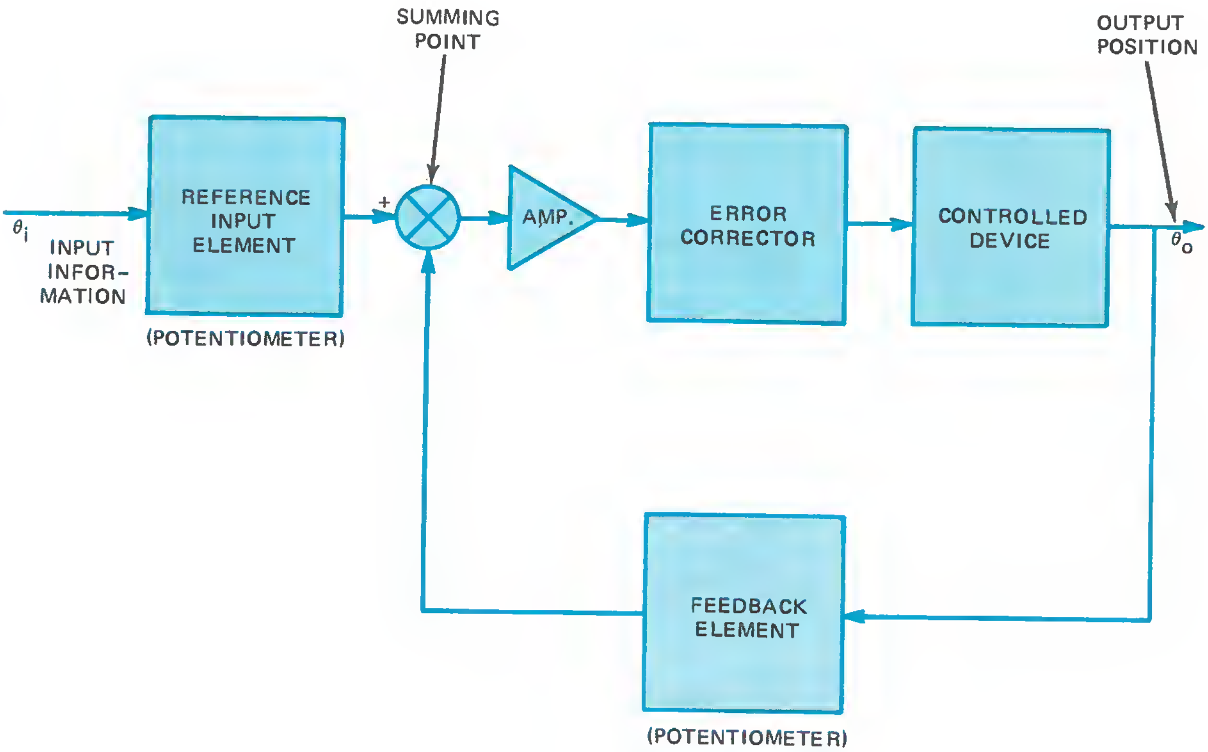


Fig. 9-1 A Servomechanism Block Diagram

The circuit diagram for the experiment is figure 9-2A and corresponds to the block diagram of figure 9-1. The potentiometers serve as the reference input and feedback elements. The amplifier is the motor generator and the error-measuring device is the summing amplifier.

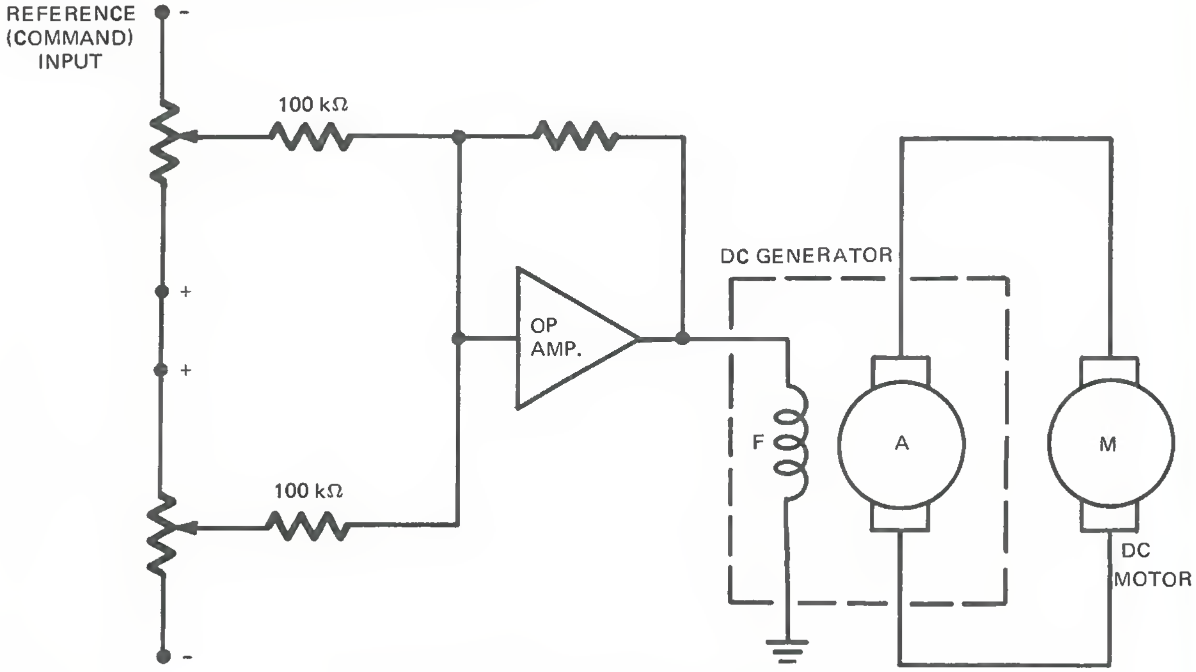


Fig. 9-2A The Experimental Setup

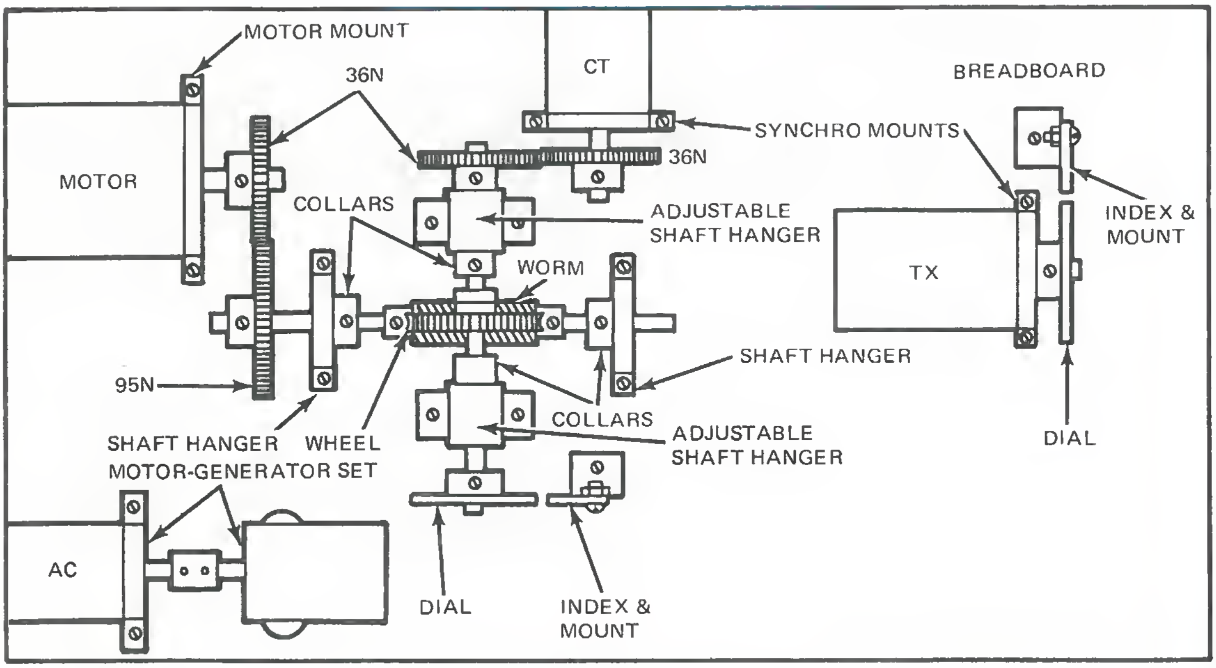


Fig. 9-2B Mechanical Assembly

MATERIALS

- 1 Breadboard with legs
- 1 Spur gear, 95N
- 2 Motor mounts
- 1 Operational amplifier
- 2 Adjustable shaft hangers
- 1 DC servomotor (PM or separately excited)
- 2 Servo potentiometers, 10 kΩ with mounts
- 3 Spur gears, 36N
- 4 Collars
- 2 360° disk dials
- 1 Spring balance
- 2 Shafts 1/4 X 4
- 1 Sine wave function generator (Low frequency)
- 1 Worm screw
- 1 Worm wheel
- 1 Lever arm, 2 in.
- 3 Resistors 100 kΩ, 2W
- 1 Motor generator (or separate units with coupling)
- 1 Power supply (0–40V)
- 1 Variable transformer (0–130V, 60 Hz)

PROCEDURE

1. Assemble the system shown in figure 9-2A and B.
2. Apply power. If the system is unstable due to excess gain, reduce the resistance of the 100 kΩ feedback resistor in the summing amplifier. You may need to fashion some type of load also.
3. Set the input and output dials to read zero degrees. Observe and record the output position for each 30° of the input dial position.
4. Hold the input shaft rigid and move the output shaft slightly to observe the dead band. Record the observed data.
5. Attach a lever arm and spring balance and measure the output torque for a difference of 5° between input and output readings. Record the results in the Data Table.
6. Repeat step 5 for 10 and 15 degree errors.
7. Remove the command input (set-point) potentiometer and connect a low frequency sine wave function generator. Observe the output with varying frequencies. **Be sure to connect sine potentiometer to an appropriate DC supply.**

ANALYSIS GUIDE. Explain your results including the reasons for different amounts of torque created wtih greater position errors. Explain the results of driving the system with a sine function generator. How could this technique be used to determine the frequency response of a servomechanism?

PROBLEMS

1. Draw a complete positioning servomechanism like the one you built in this experiment but use a magnetic amplifier instead of an electromechanical one. Remember that it must be able to distinguish between direction of errors and it may require one or more saturable reactors to accomplish the desired control.

2. Assume an error in one direction and give a detailed description of how the error is corrected.

3. Assume an error in the opposite direction from problem 2 and explain how your system corrects for it.

4. Explain what you would do if the system were unstable and tended to oscillate.

5. Explain what you would do to your system if the dead band were too wide.

Input Shaft Angle	Output Shaft Angle
0°	0°
30°	
60°	
90°	
120°	
150°	
180°	
210°	
240°	
270°	
300°	
330°	
360°	

Dead Band ____________

Output Torque: 5° error ______ in.-oz
10° error ______ in.-oz
15° error ______ in.-oz

Fig. 9-3 The Data Table

experiment 10 OPTICAL POWER STEERING UNIT

INTRODUCTION. This experiment illustrates a follow-up type of control unit that could have application as a power steering unit. Other applications are possible where tracking of two mechanical units is desired.

DISCUSSION. This experiment involves a photocell of the photoresistive (or photoconductive) type. As light strikes the surface of the photocell, conductors are liberated, reducing the resistance. If the cells are placed in a bridge circuit, as shown in figure 10-1, the bridge can be used as an error-measuring device. With no light or equal amounts of light on the two photocells, their resistance would be about the same. If the resistors R_1 and R_2 are equal, the bridge will be balanced and there will be no output signal.

If more light falls on PC_1 than on PC_2, the resistance of the PC_2 will be lower, and with the polarities shown (for the positive half cycle), the drop across PC_2 will be greater than PC_1, making terminal 1 more positive than terminal 2. If PC_2 had more light on it, its resistance would be the lower of the two, making terminal 2 of the output more positive than terminal 1. The important point is that a 180° phase difference is realized when illumination is changed from one cell to the other.

When this device is used to measure an error, the same amount of light on each cell causes the bridge to be balanced. When more light impinges on one than on the other, an error signal is produced. The error contains information telling the direction of the error by its phase. This would allow a controller such as a two-phase AC motor to be used in correcting the error.

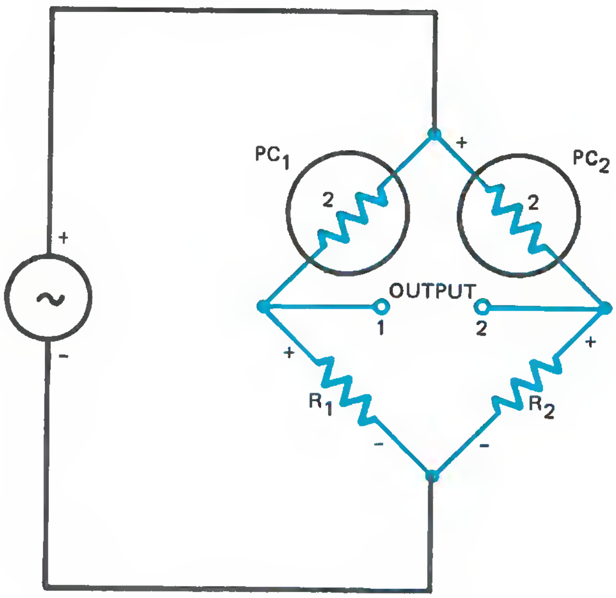


Fig. 10-1 The Bridge Circuit

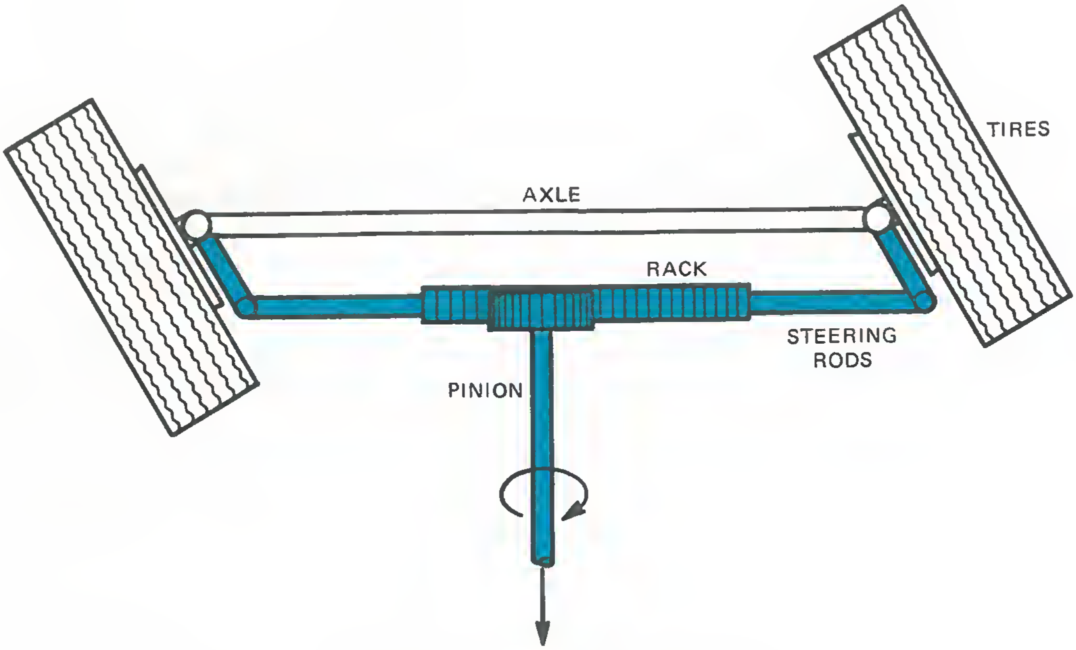


Fig. 10-2 Rack to Pinion Steering

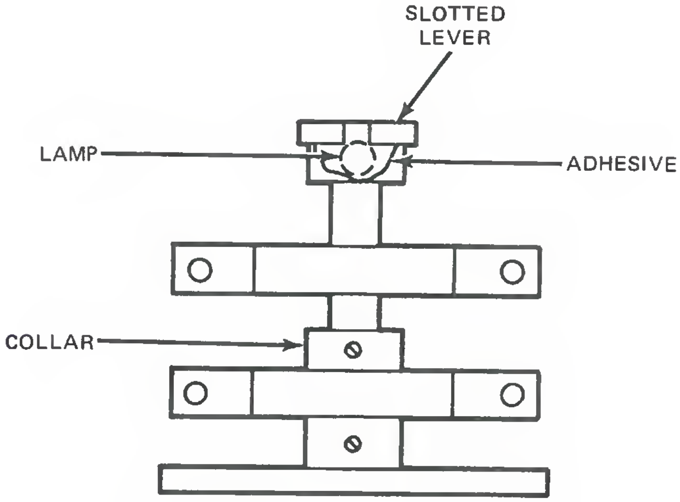
This experiment is a simplified model of a possible power steering unit in a car or tractor. The calibrated dial we will use represents the steering wheel and the steering is accomplished by a rack and pinion type of steering popular on some European cars. Rack and pinion steering is accomplished as shown in figure 10-2.

MATERIALS

1 Breadboard with legs and clamps
2 Bearing plates with spacers
1 Worm and worm wheel
1 Spur gear, 1 in. diameter
1 Spur gear, 2 in. diameter
1 Rack and pinion 3/4 in.
4 Bearing mounts with bearings
2 Shaft hanger (adjustable), with bearings
1 Shaft hanger (1-1/2 in.), with bearings
3 Shafts, 1/4 X 4
1 Shaft, 1/4 X 2
1 360° disk dial
1 Dial index with mounts
1 Geneva mechanism (or other gear device about 2 in. diameter with holes).
1 Resistor, 120 kΩ, 1/2W
1 Slotted lever arm, 2 in.
3 Collars
3 Dial index mounts
1 Rigid coupling for 1/4 in. shafts
1 Servoamplifier
2 Capacitors, 5 μF
2 Photocells, Clairex CL904 or equivalent
1 Lamp, NE2 or equivalent
1 Resistor, 27 kΩ, 1W
1 Potentiometer, 50 kΩ, 2W
1 Oscilloscope
1 Small amount of gum rubber like that used to seal around air conditioners. (Modeling clay will also work satisfactorily)
1 DC power supply (0–40V)
1 Variable transformer (0–130V, 60 Hz)

PROCEDURE

1. Connect the mechanism shown in figure 10-3A, B, C and D.
2. Wire it according to figure 10-4 but do not apply power.
3. Place the lamp in the slotted lever arm so that when the wheel is turned the light will shine through the holes in the geneva wheel. Hold the lamp in place with the gum rubber.



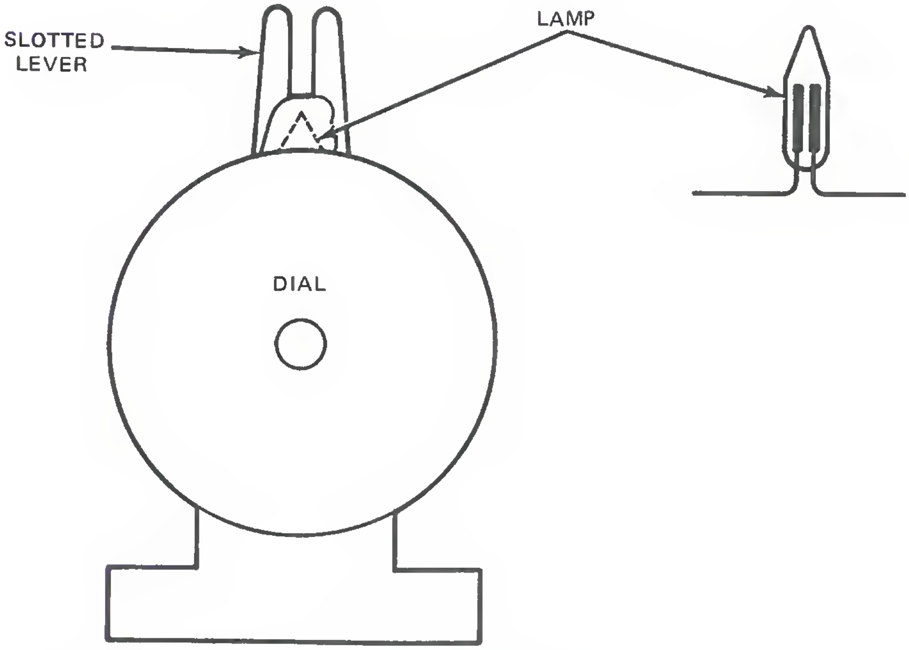


Fig. 10-3(A) The Experimental Mechanism

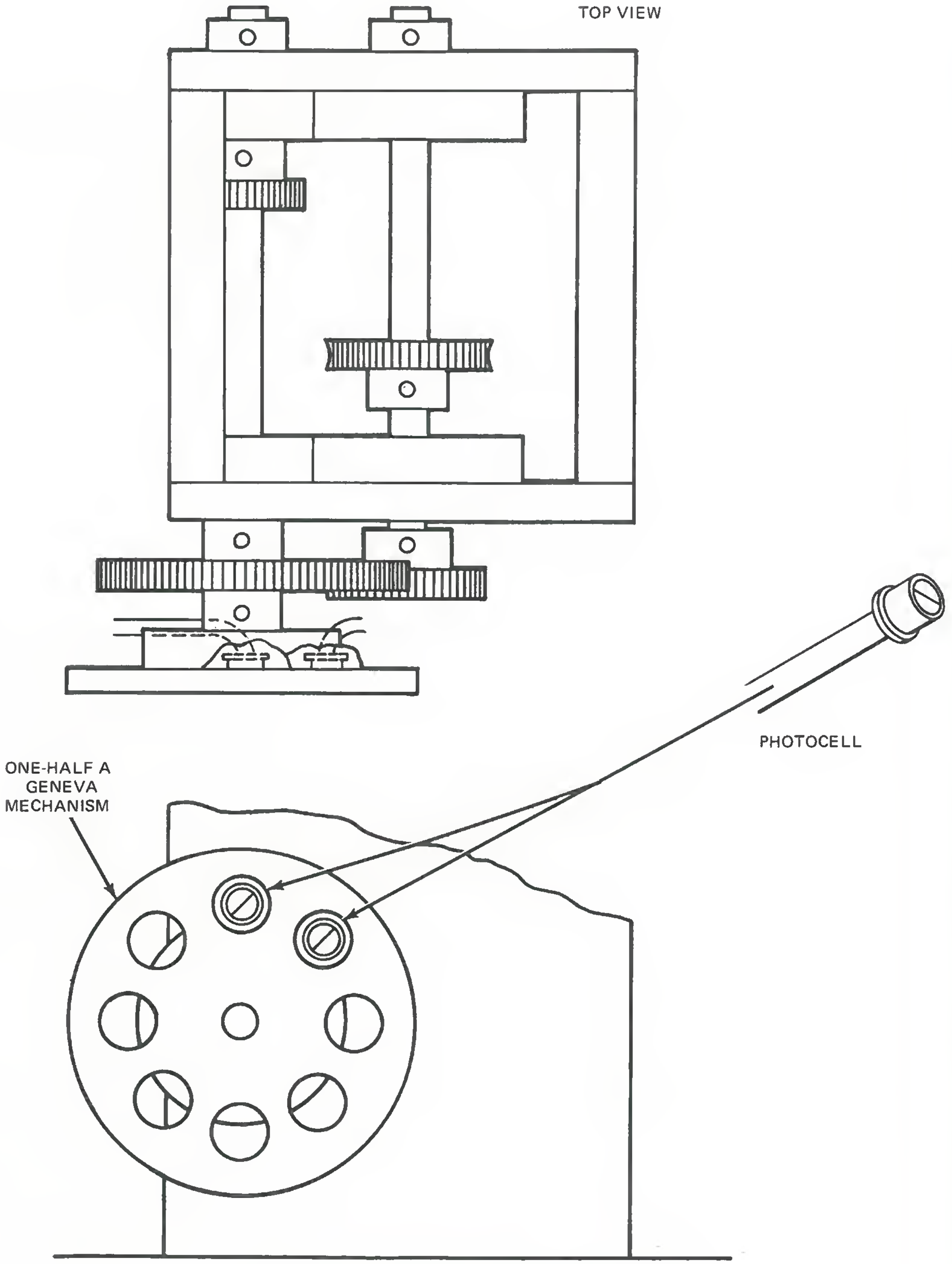


Fig. 10-3(B) The Experimental Mechanism

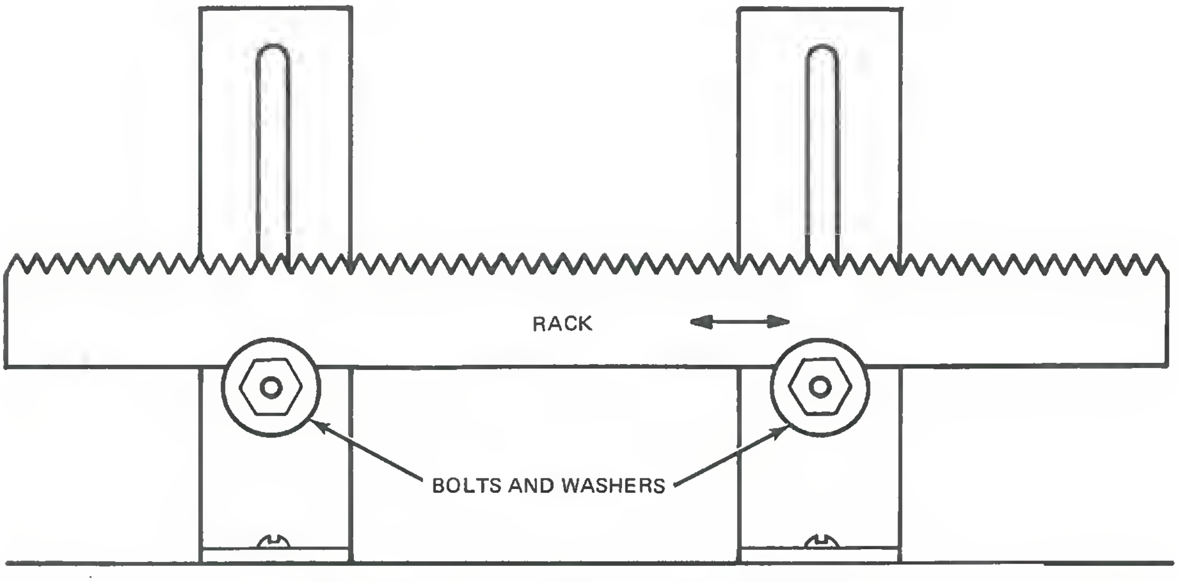


Fig. 10-3(C) The Experimental Mechanism

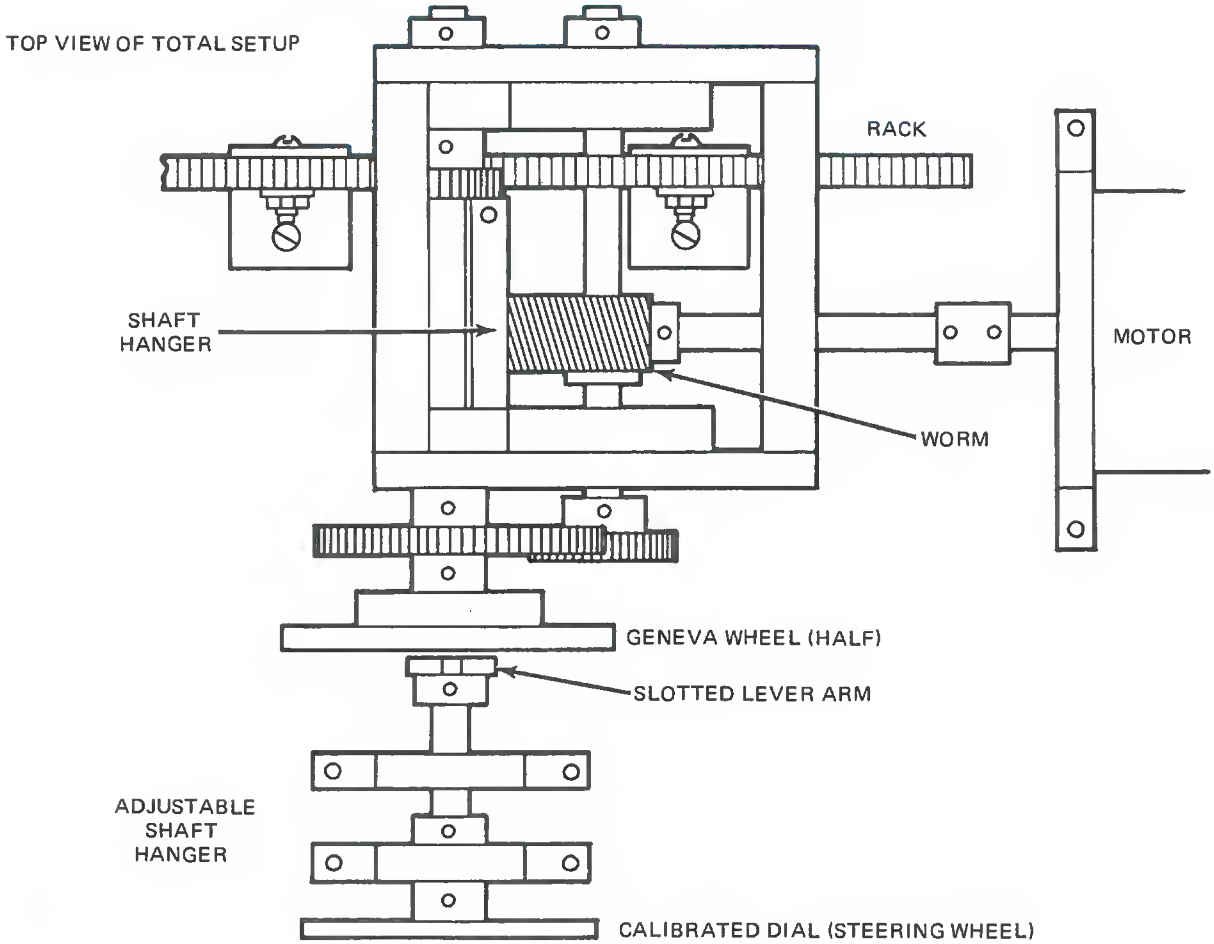


Fig. 10-3(D) The Experimental Mechanism

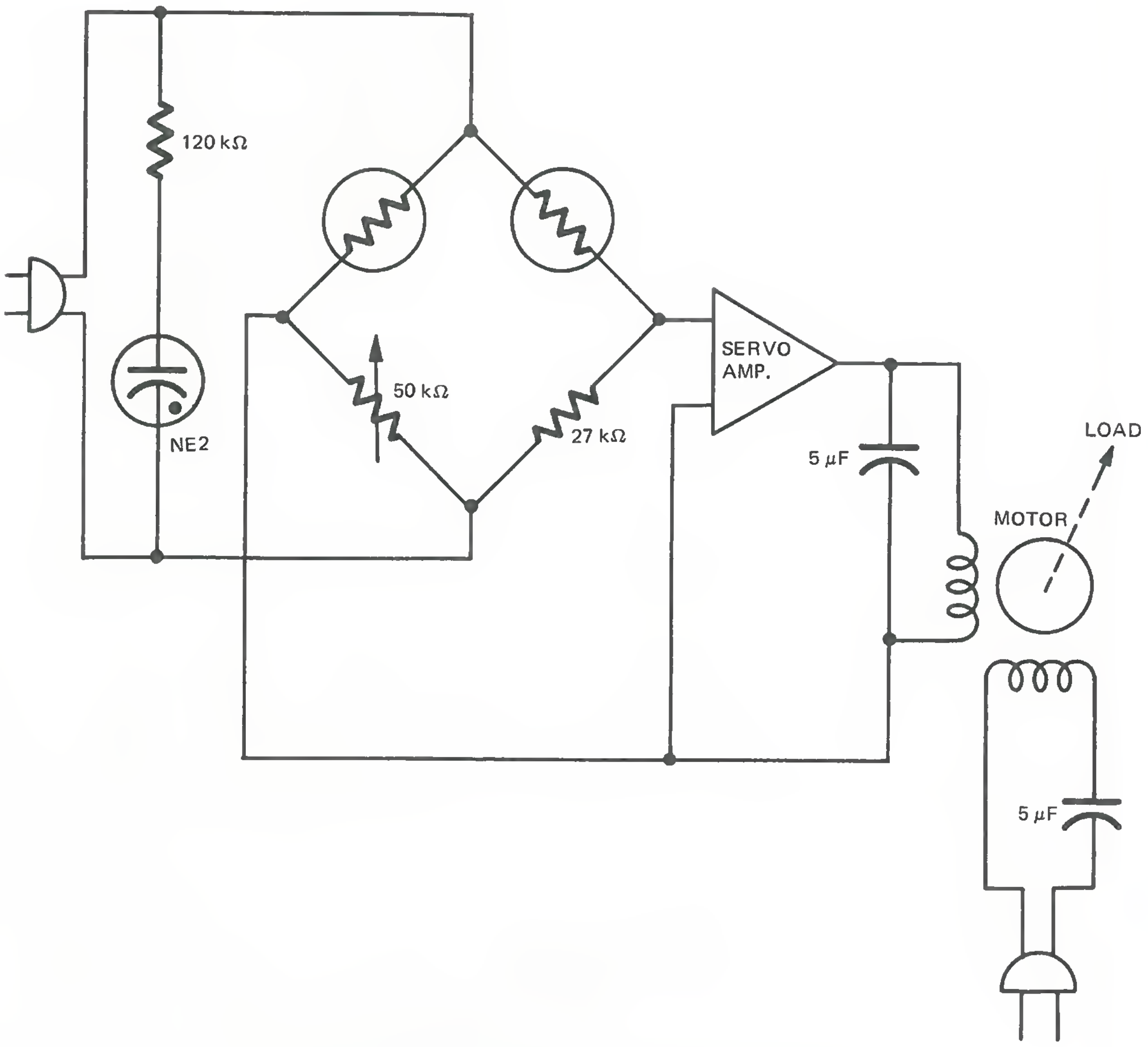


Fig. 10-4 Circuit Diagram of Experimental Setup

4. Put the photocells in two adjacent holes of the geneva gear and secure with gum rubber.
5. Leave considerable slack in the wires going to the photocells and lamp to allow for rotation.
6. Place the slotted lever as close as possible to the photocells without creating excessive friction.
7. With the motor disconnected and the light source halfway between the photo cells, adjust the variable resistor in the bridge for minimum output from the servoamplifier. **Be sure the gain of the servoamplifier is high during this step.**
8. Use "line" synchronization and observe the waveform at the output of the servoamplifier as you turn the steering wheel (calibrated dial) back and forth.

9. Reduce the gain of the servoamplifier to minimum. Connect the circuit and increase the gain until reasonable performance is acquired.

10. Test the apparatus for operation. Vary the gain and frictional forces and observe the system operation.

ANALYSIS GUIDE. Explain the overall system and discuss the results of your experimentation.

PROBLEMS

1. Explain how the problem of the wires connecting to the lamp and photocells can be solved if the system were to be used.
2. Explain the major danger of using this system alone on a car. For example, what would happen if you lost power to the system?
3. What would be some possibilities if a greater number of revolutions of the steering wheel is desired for turning from one extreme wheel position to the other?
4. Could this system be used with an infrared instead of optical exciter and detectors? Explain how. Look up a suitable thermistor in a parts catalog.
5. Draw the same system using an incandescent lamp as the source and the two thermistors from problem 4.

experiment 11 INTRODUCTION TO DIGITAL TEMPERATURE CONTROLS

INTRODUCTION. The advent of inexpensive integrated circuits has allowed the use of digital control techniques where only analog systems were once economically possible. In this experiment we will examine some basic concepts of digital control.

DISCUSSION. Digital systems involve pulses which may contain information in the repetition rate, pulse width, amplitude or position of the pulses. These pulses, with their attendent information, tell the system how to respond. For closed loop operation, the error signal changes the pulse in such a way that when there is no error, the pulse information causes no change in the controlled device.

Figure 11-1 is the block diagram of a closed loop digital servo system.

The clock of figure 11-1 tells the counter *how long* to count the pulses from the variable frequency oscillator. Since this is a fixed time determined by the clock, the number of cycles from the variable frequency oscillator occurring during this time is an indication

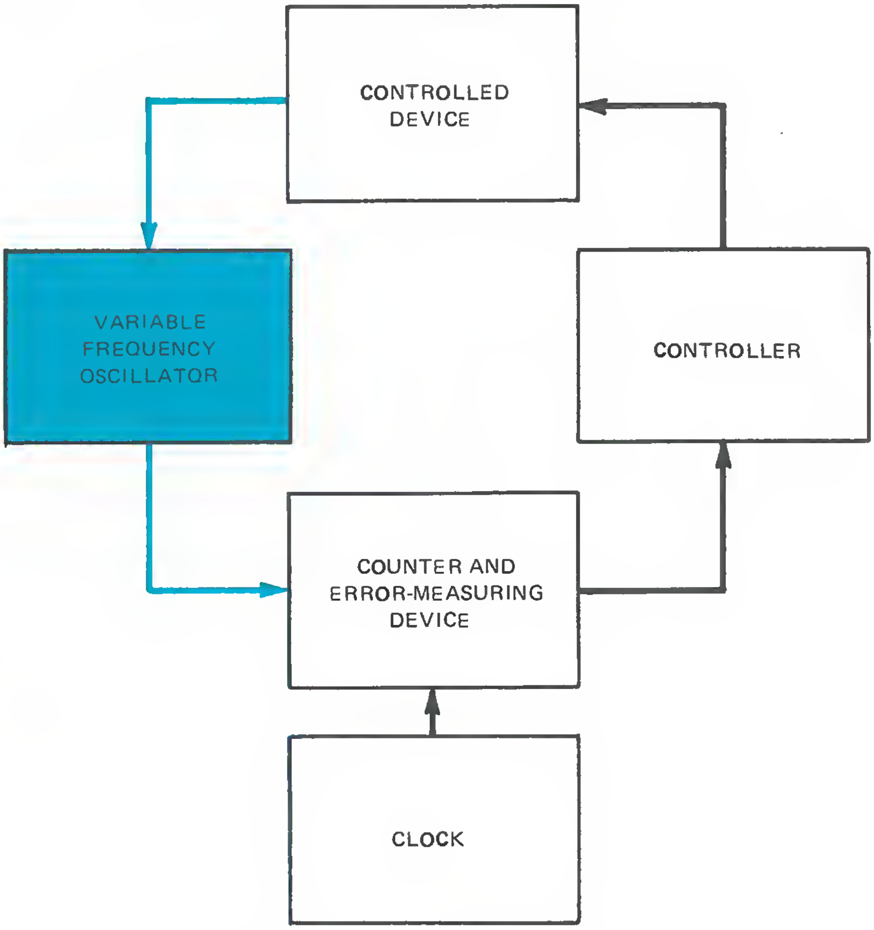


Fig. 11-1 A Digital Control System

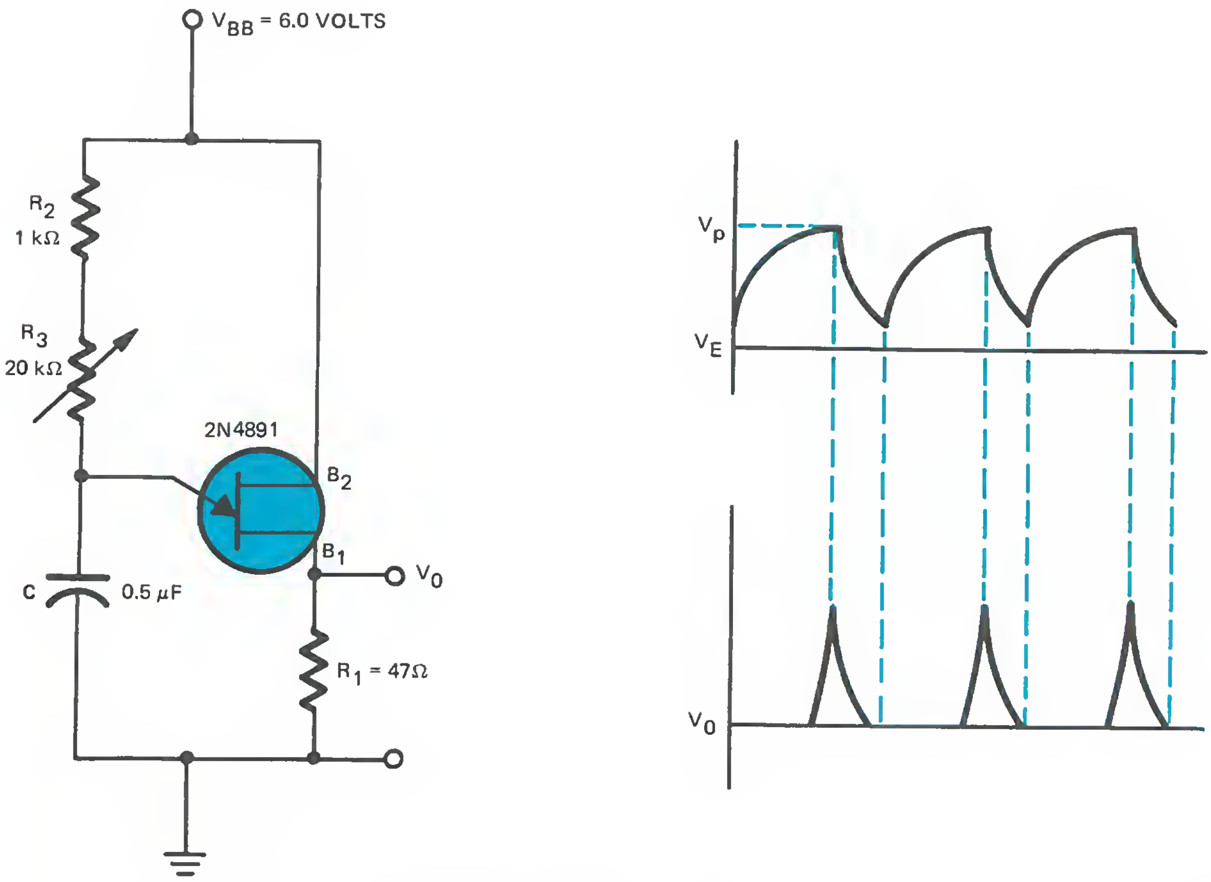


Fig. 11-2 UJT Oscillator

of the condition of the controlled device. This is because the controlled device is being used to determine the frequency of the variable frequency oscillator.

If the count that accumulates in the counter during a cycle of the clock is the predetermined correct amount, the controller does nothing. However, if the count is wrong, the controller would be activated to correct the error which would then produce the correct count, stopping the controller. This general description fits the concept of a closed-loop servomechanism where pulses are used in error sensing.

In this experiment we will be concerned with the variable frequency oscillator.

Figure 11-2 is the circuit diagram of a unijunction transistor (UJT) oscillator. The firing or peak potential, V_p, of the UJT is given by

$$V_p = \eta V_{BB}$$

where η is the intrinisic standoff ratio (a constant for any given UJT which varies from about 0.5 to 0.85 for most devices). V_{BB} is the supply voltage.

Once the capacitor charges to this voltage the UJT "fires", allowing the capacitor to discharge through R_1 and the base one - emitter circuit, generating the output voltage

shown. The output frequency, f, is given approximately by

$$\boxed{f = \frac{1}{R_E C}}$$

where R_E is the total emitter resistance. Thus

$$R_E = R_2 + R_3$$

Since R_3 is a variable resistor (could be varied by temperature, light or mechanically) this circuit is the one referred to in the block diagram of figure 11-1 as the variable frequency oscillator.

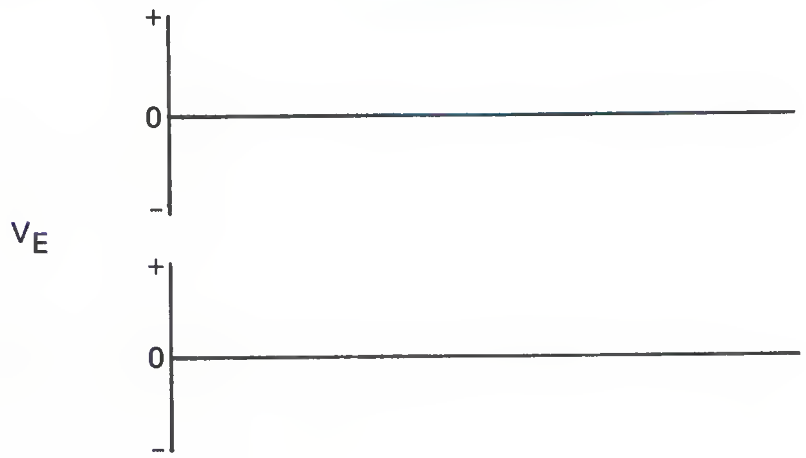
MATERIALS

- 2 Potentiometers, 10 kΩ, 2W, linear, or a decade resistance box
- 1 Capacitor, 0.5 μF, 6V
- 1 UJ Transistor, 2N4891 or equivalent
- 1 Resistor, 1 kΩ, 1/2W
- 1 Resistor, 47Ω, 1/2W
- 1 DC power supply (0–40V)
- 1 Oscilloscope
- 1 Sheet of graph paper

PROCEDURE

1. Connect the circuit of figure 11-2.
2. Observe and record the waveshapes at the emitter and base one with R_E set approximately at mid resistance.
3. Calculate the approximate frequency for the values of R_E (which is $R_2 + R_3$) shown in the Data Table.
4. Measure and record the output frequency in pulses per second, PSS, at the resistance shown in the Data Table.
5. Plot a curve of frequency vs R_E and plot both calculated and measured frequencies on the graph.

Waveshapes (Fig. 11-2)



R_E	Calculated Frequency	Measured Frequency
1 kΩ		
2 kΩ		
4 kΩ		
8 kΩ		
10 kΩ		
12 kΩ		
14 kΩ		
16 kΩ		
18 kΩ		
20 kΩ		

Fig. 11-3 The Data Table

ANALYSIS GUIDE. Explain why changing R_E changes the frequency of operation and why the measured frequency is different from the calculated value.

PROBLEMS

1. Use your graph and determine the value of the resistance, R_3, for a frequency of 75 Hz.
2. Determine the resistance of R_3 for a desired frequency of 150 Hz.
3. Redraw the circuit of figure 8-2 but show the resistor R_2 as a photocell (photo-resistive type) with a resistance of 10k ohms with a given light intensity.
4. What would be the value of R_3 if a frequency of 75 Hz were desired when the photocell resistance is 10k ohms? (Use information from problem 1.)
5. What would be the value of R_3 if a frequency of 150 Hz were desired under the condition where the photocell resistance is 10k ohms?
6. If the light intensity on the photocell in the previous problem should increase so that the resistance changed from 10k ohms to 5k ohms, how much would the output frequency change if R_3 were held constant at 5k ohms?
7. Name two other transducers whose resistance change with some physical quantity that might be used in place of the photocell.

experiment 12 TEMPERATURE CONTROL CLOCK

INTRODUCTION. An electronic clock is often called the heart of the digital control system. In this experiment we will examine a method of making a clock from logic blocks.

DISCUSSION. A multivibrator is very often used in a digital control system to provide pulses, and as a device to synchronize the overall operation of the system. This synchronizing multivibrator is called the clock. The clock used in this experiment will be made from two NOR circuits.

NOR comes from the combination of the words NOT – OR, in which the OR function is performed then inverted. Remember that the output of a 3-input OR circuit is a 1 when input A or input B or input C is a 1. The truth table of figure 12-1 illustrates the OR function. The output is a 1 when any of the inputs is a 1. Note what happens if you invert the OR. By inversion we mean that when the input is high (a 1) the output is low (a 0) or vice versa. To do this in the table, we change the 1s to 0s and 0s to 1s. This inverted OR function is the truth table for the NOR function. Another way of arriving at the same result is to OR the variables:

$$A + B + C = \text{Output of OR}$$

Then invert them:

$$\overline{A + B + C} = \overline{\text{Output of OR}} = \text{NOR}$$

By Demorgan's Theorem we invert each term and change all ORs to ANDs and vice versa in order to invert a quantity.

$$\boxed{\bar{A} \times \bar{B} \times \bar{C} = \text{NOR}}$$

A	B	C	OR Output	Inverted NOR Output
0	0	0	0	1
0	0	1	1	0
0	1	0	1	0
0	1	1	1	0
1	0	0	1	0
1	0	1	1	0
1	1	0	1	0
1	1	1	1	0

Fig. 12-1 Truth Table for OR and NOR

$\overline{A}$	$\overline{B}$	$\overline{C}$	NOR Output
1	1	1	1
1	1	0	0
1	0	1	0
1	0	0	0
0	1	1	0
0	1	0	0
0	0	1	0
00	0	0	0

Fig. 12-2 Truth Table for a NOR Function

The truth table for this expression is shown in figure 12-2. The $\overline{A}$ column, for example, is attained by changing the A column of figure 12-1 so that the 1s are 0s and 0s are 1s. The output is accomplished by performing the AND operation. Notice that the output is the same as the inverted column of figure 12-1 which demonstrates by induction that

$$\overline{A + B + C} = \overline{A} \cdot \overline{B} \cdot \overline{C} = \text{NOR function}$$

A typical digital control system is shown in figure 12-3 in block diagram form.

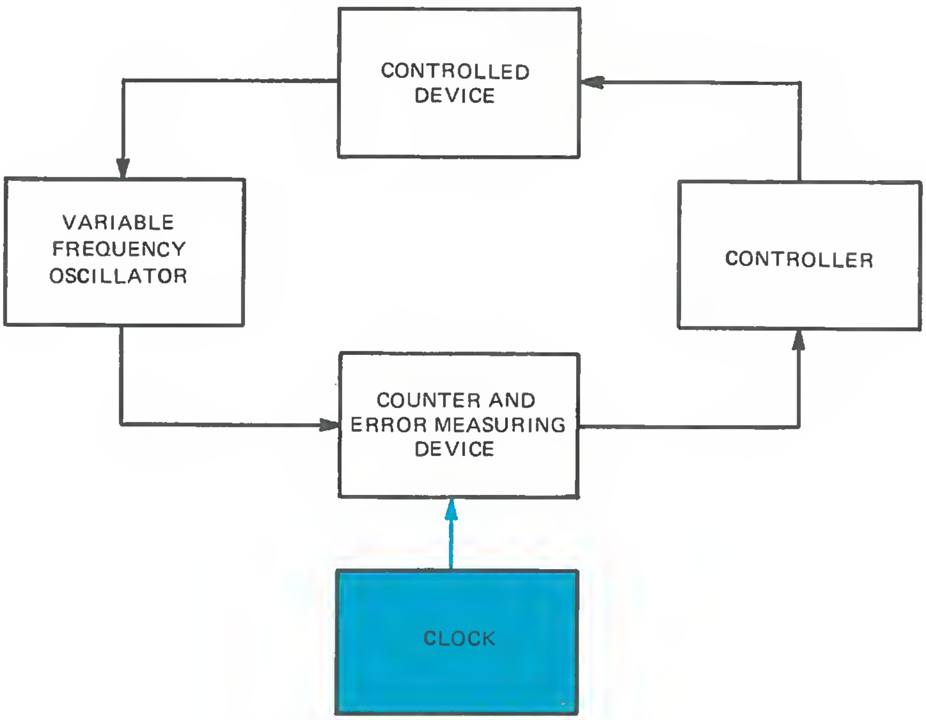


Fig. 12-3 A Digital Control System

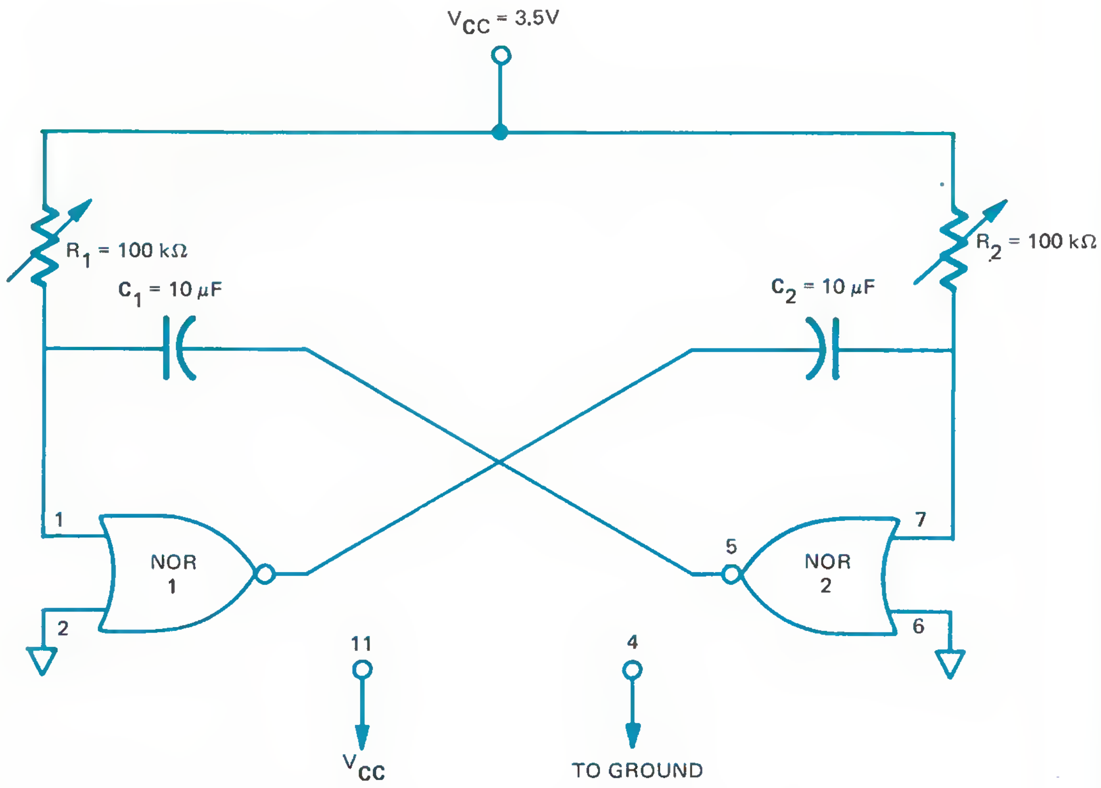


Fig. 12-4 An Integrated Astable Multivibrator Clock

The clock of figure 12-3 tells the counter *how long* to count the pulses from the variable frequency oscillator. Since this is a fixed time as determined by the clock, the number of cycles from the variable frequency oscillator occurring during this time is an indication of the condition of the controlled device. This is because the controlled device is being used to determine the frequency of the variable frequency oscillator.

If the count that accumulates in the counter during a cycle of the clock is the predetermined correct amount, the controller does nothing. However, if the count is wrong, the controller would be activated to correct the error which would then produce the correct count, stopping the controller. This general description fits the concept of a closed-loop servomechanism where pulses are used in error sensing.

You have studied several types of astable (free-running) multivibrators but figure 12-4 may be a version that you have not previously encountered. This one was chosen because the low price of the integrated circuit makes it economical, especially since it contains two other NOR circuits that will be used in the total system to be built later.

The circuit of figure 12-4 is actually a collector-coupled astable multivibrator using the transistors of the integrated circuit. The circuit diagram and integrated circuit layout are shown in figure 12-5. The output frequency, f, is given approximately by

$$\boxed{f \cong \frac{1}{1.4RC}}$$

where the output is a symmetrical square wave.

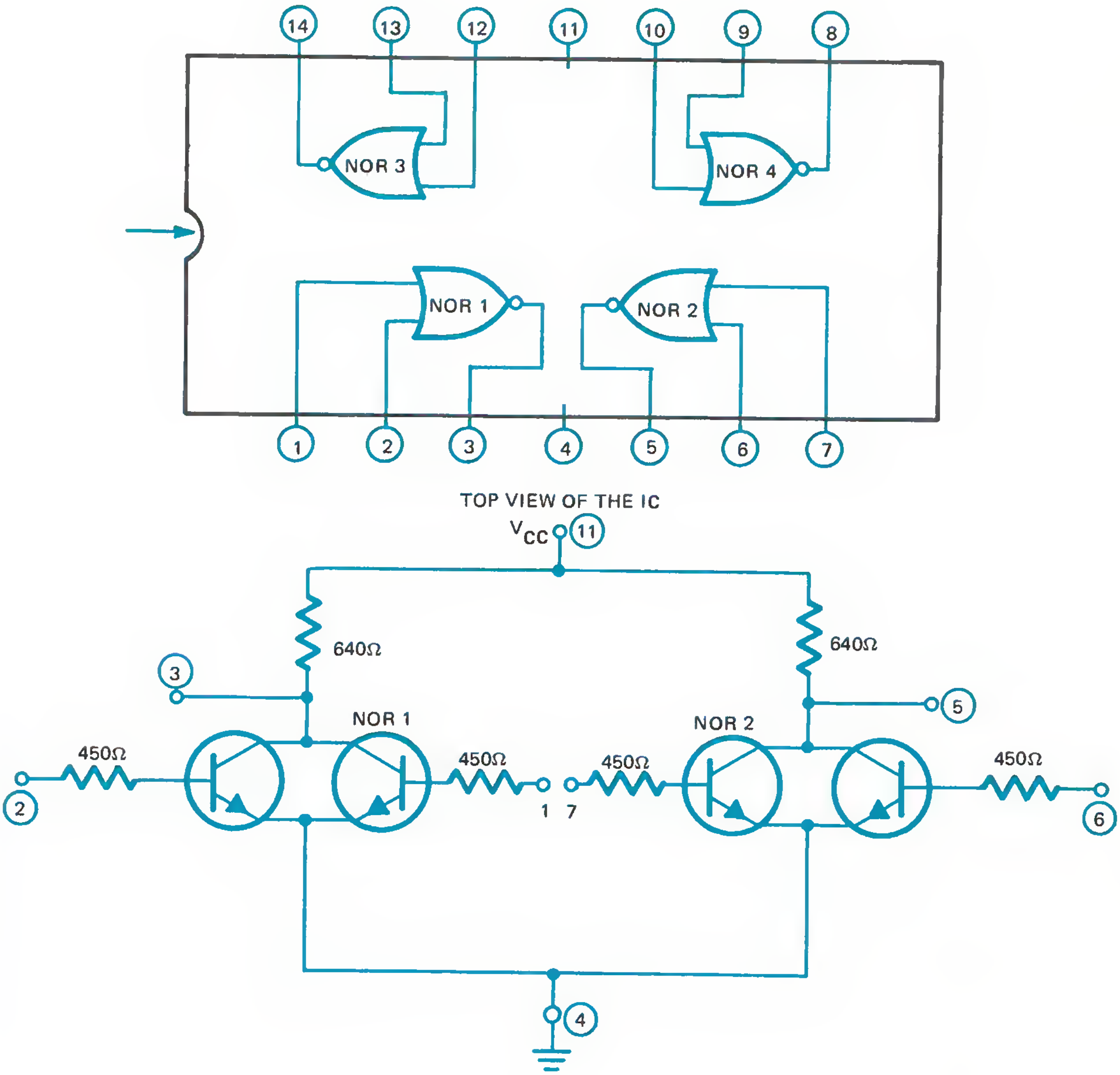


Fig. 12-5 Block Diagram and Circuit of the IC

MATERIALS

1 Quad, 2-input NOR integrated circuit, MC 724P or equivalent
2 Capacitors, 10 μF, 6V
1 DC power supply (0 - 40V)
1 Oscilloscope
2 Potentiometers, 100 kΩ, 1W, linear or a decade resistance box

PROCEDURE

1. Connect the IC so that pin 4 goes to common and pin 11 to the 3.5V supply.

Input A (pin 1)	Input B (pin 2)	Output (pin 3)
0	0	
0	3.5	
3.5	0	
3.5	3.5	

(A)

A	B	Output
0	0	
0	1	
1	0	
1	1	

(B)

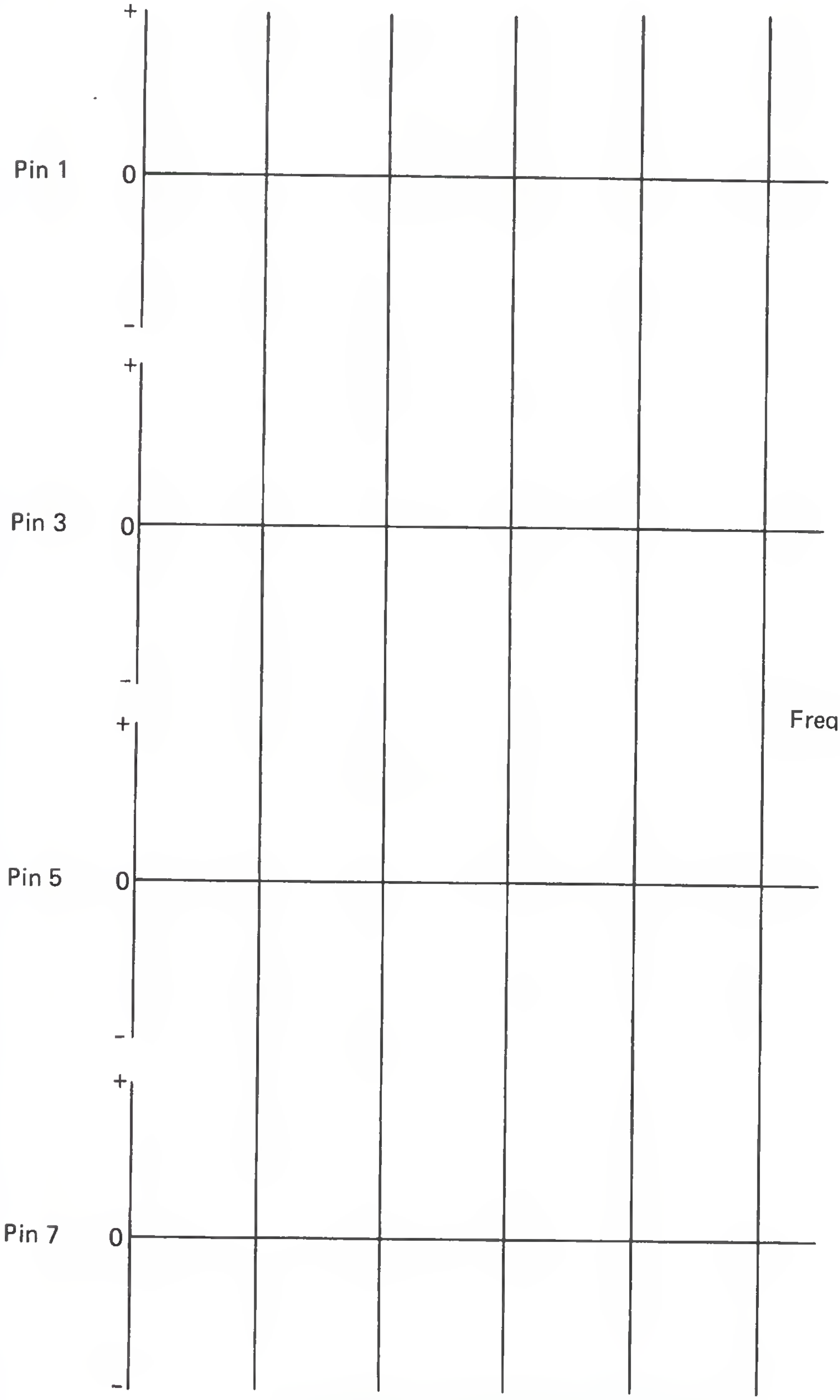
Fig. 12-6 Data for the NOR Logic

2. Complete the data table for the NOR 1 (pins 1, 2 and 3) circuit and record the output voltage in figure 12-6A. Zero voltage means to ground the input
3. Consider voltage less than 1 volt a *zero* and more than 1 volt a *one* and complete the truth table of 12-6B.
4. Connect the circuit of figure 12-4. Set the resistors to 10 kΩ. **Be sure pins 11 and 4 are connected to V_{CC} and ground, respectively.**
5. Record the output waveshapes at pins 1, 3, 5 and 7 in figure 12-7. Use external sync so that the phase relationship of the waves can be determined.
6. Adjust the potentiometers one at a time and observe the nonsymmetrical output waveform on the oscilloscope.
7. Adjust the variable resistors R_1 and R_2 to get the waveform of figure 12-8. There will be interaction between the settings so it will take considerable adjustment and readjustment to get the desired results. Output can be from either pin 5 or pin 3.
8. Carefully measure the resistance of each potentiometer and record their values in figure 12-8. **Be sure to indicate where (from which pin) you got your final desired waveshape.**

ANALYSIS GUIDE. In analyzing the results of these data you should consider whether or not they agree with the material presented in the discussion.

PROBLEMS

1. Make a truth table for a three-input AND circuit. Call the inputs, A, B and C.
2. Complement (invert) the output of the truth table of problem 1. What function is represented from input to output?
3. If complements (inverses) of the three inputs are available, show and explain how a NAND circuit may be used to satisfy the OR operation of the original three inputs A, B, and C.

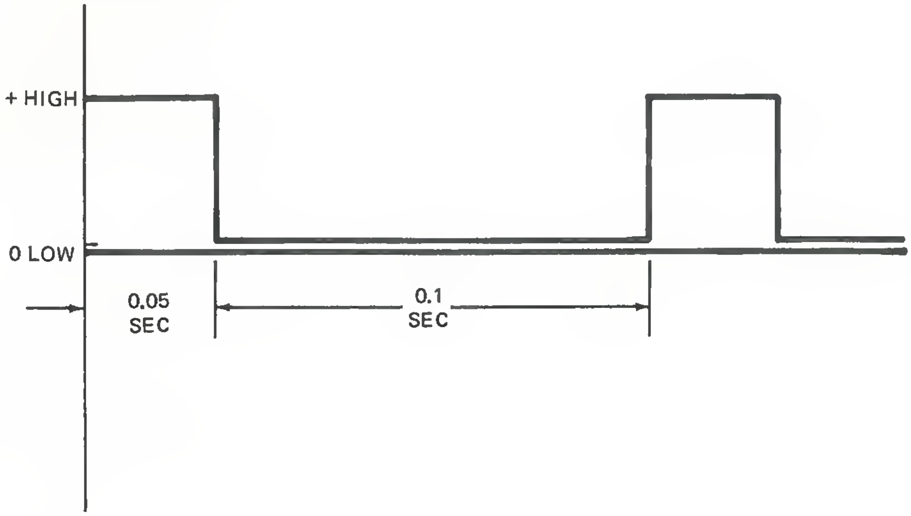


Frequency = ________ Hz

Fig. 12-7 Data Table for Multivibrator

4. Calculate the value of resistors R_1 and R_2 required when $C_1 = C_2 = 1\ \mu F$ to produce an output frequency of 10 kHz.

5. What size capacitors, C_1 and C_2, would be ideal for use with 33 kΩ resistors, R_1 and R_2, if a frequency of 5 kHz was desired?



R_1 = ____________________ ohms

R_2 = ____________________ ohms

Fig. 12-8 Data for Nonsymmetrical Output

experiment 13 MANUAL TEMPERATURE CONTROL

INTRODUCTION. Digital controls are employed in a great variety of industrial systems. In this exercise we will examine the operation of a simple oven, with emphasis on sensing and controlling its temperature.

DISCUSSION. A basic type of digital control can be represented by the block diagram of figure 13-1. This diagram represents a closed-loop digital servomechanism.

The clock of figure 13-1 tells the counter *how long* to count the pulses from the variable frequency oscillator. Since this is a fixed time determined by the clock, the number of cycles from the variable frequency oscillator occurring during this time is an indication of the condition of the controlled device. This is because the controlled device is being used to determine the frequency of the variable frequency oscillator.

If the count that accumulates in the counter during a cycle of the clock is the predetermined correct amount, the controller does nothing. However, if the count is wrong, the controller is activated to correct the error which would then produce the correct count, stopping the controller. This general description fits the concept of a closed-loop servomechanism where a count of pulses is used in error sensing.

This experiment concerns itself primarily with the controlled device. The controlled device will be an oven heated by a 75-watt lamp while the temperature is monitored by a thermistor.

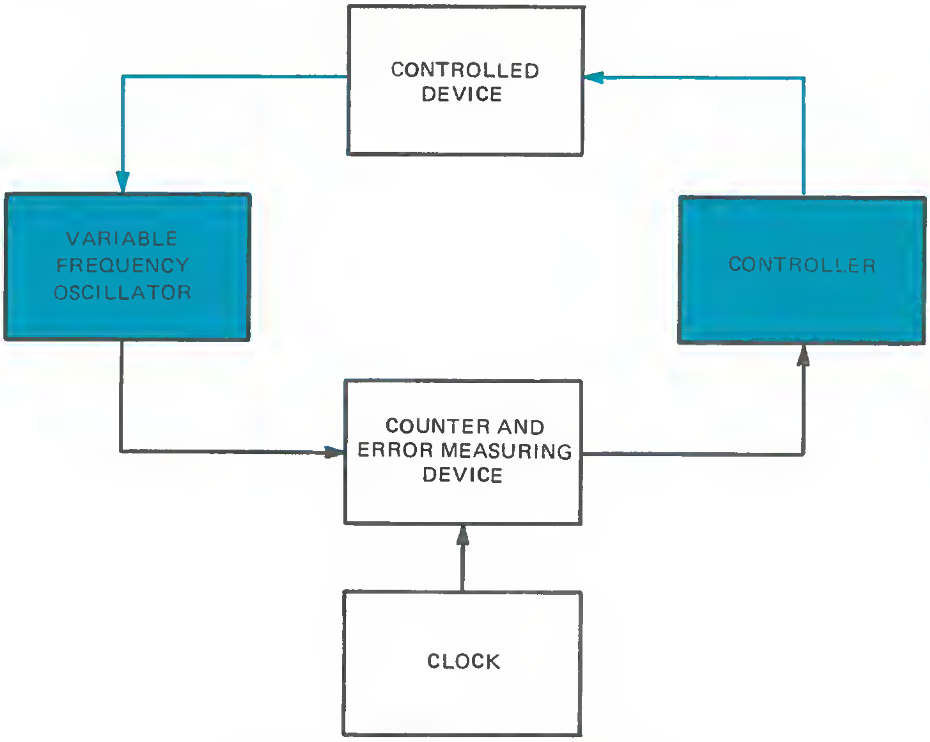


Fig. 13-1 A Digital Control System

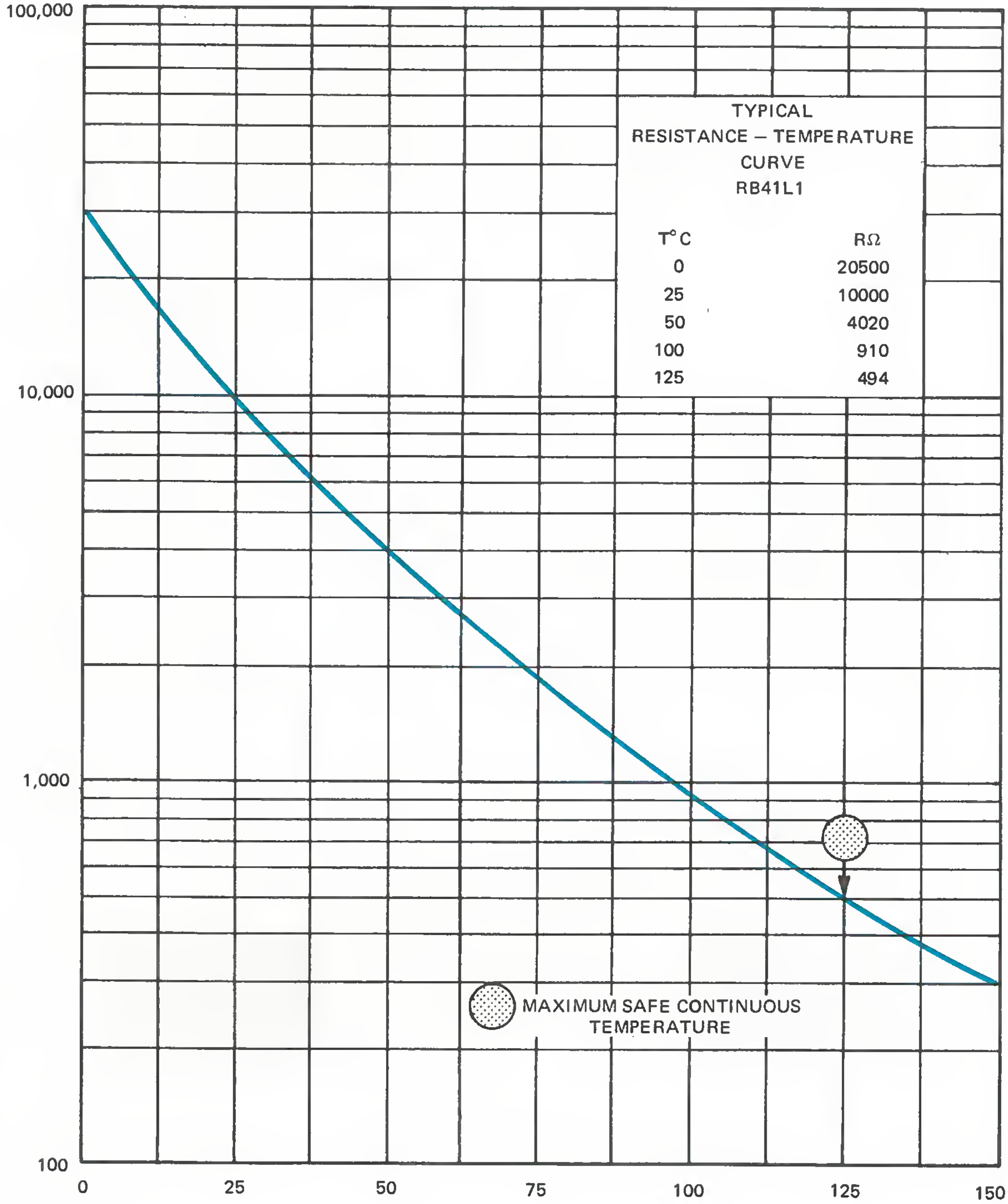


Fig. 13-2 Thermistor Curve

The thermistor to be used in this experiment is a 10k ohm (at 25°C) model that has a negative temperature coefficient of resistance. A negative temperature coefficient means that as temperature goes up, the resistance goes down and vice versa. Figure 13-2 is the response curve for the thermistor to be used in this experiment.

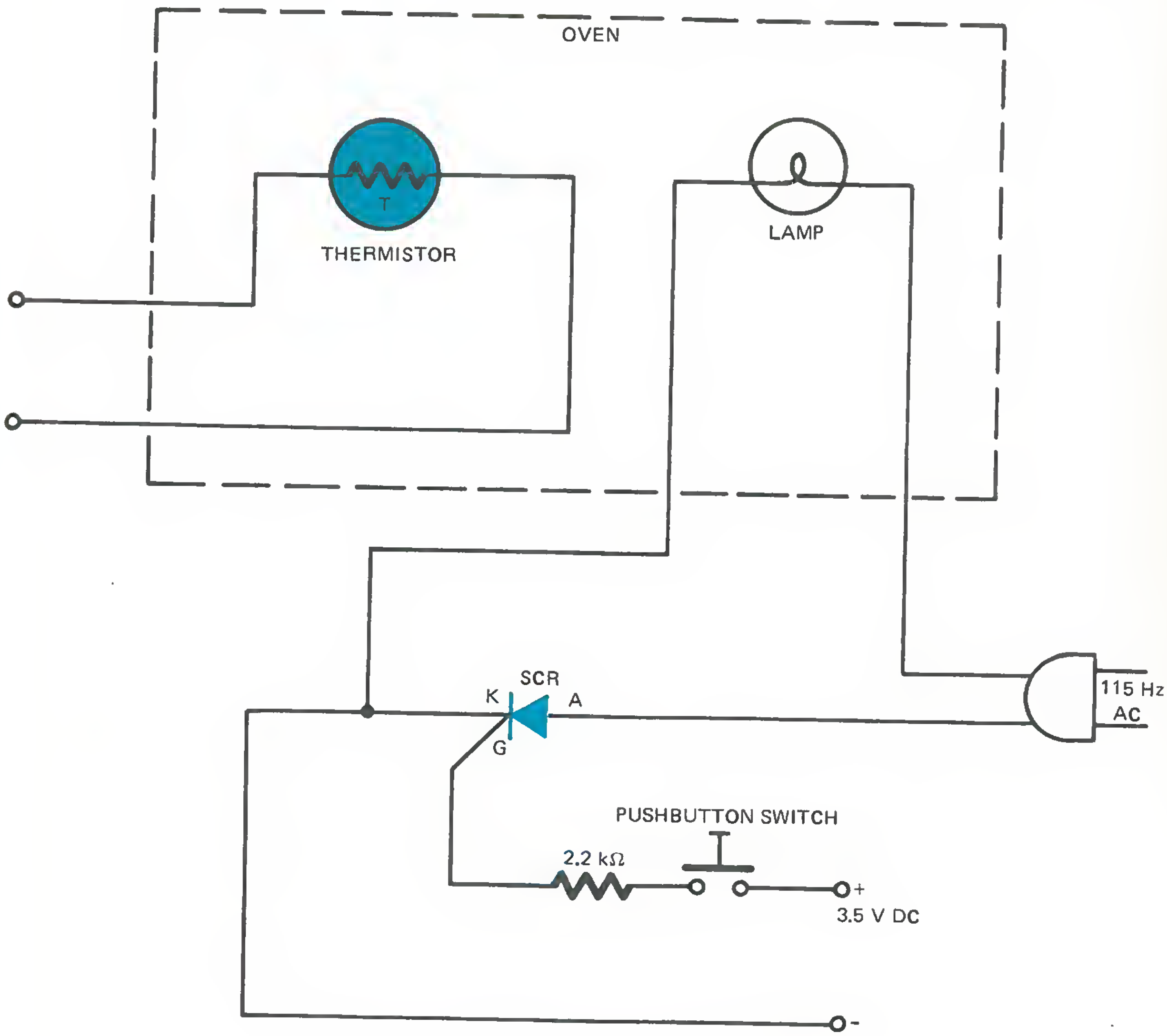


Fig. 13-3   Experimental Setup

The experimental setup is shown in figure 13-3. The thermistor resistance will change with temperature and the temperature will increase while the lamp is lighted. The lamp is turned on and off with the pushbutton switch because the gate is connected to the 3.5-volt supply turning on the SCR. Since the SCR has alternating current applied to the anode-cathode circuit, it recovers every half cycle (when the anode is negative and cathode positive) so the switch will, in effect, turn it both off and on. The advantage of this particular arrangement (instead of the switch being directly in the AC line) is the low switch current. The low control current requirement will allow integrated circuit logic blocks to be used later for control of the lamp.

The lamp only conducts current for half the time (on one half cycle) but even though the power is down to half, note when you run the experiment that about 70% brightness is realized with half power.

MATERIALS

- 1 Oven (use a cardboard box such as a shoe box)
- 1 Lamp, 75W, 115V, with socket
- 1 Thermistor, bead type 10 kΩ, type RB41L1 or equivalent
- 1 DC power supply (0 – 40V)
- 1 Pushbutton SPST switch
- 1 Resistor, 2.2 kΩ, 1/2W
- 1 SCR, GE type C22B or equivalent
- 1 Line cord
- 1 VOM or FEM

PROCEDURE

1. Connect the circuit of figure 13-3.
2. Push the button and observe that the light comes on.
3. Measure the initial resistance of the thermistor with an ohmmeter and record the value in the space provided in the data table.
4. Use the curve of figure 13-2 to determine the room temperature.
5. Hold the switch on so that the light remains ON for about 10 seconds. Quickly observe the thermistor resistance. Record this value in the data table.
6. Use the graph of figure 13-2 to determine the temperature.
7. Repeat this process for the times listed on the data table.

Thermistor Resistance ______________________

Room Temperature ______________________

ANALYSIS GUIDE. Explain the basic operation of the circuit. Explain the effect of the time delay of the thermistor on the results. Also discuss how different lengths of time between the steps in the experiment might affect the thermistor readings.

Time	Thermistor Resistance	Temperature
10 sec		
30 sec		
50 sec		
60 sec		
2 min		
3 min		

Fig. 13-4 The Data Table

PROBLEMS

1. An ohmmeter uses current to measure resistance; power is I^2R. Explain what effect high ohmmeter (or other) currents would have on the temperature of the thermistor and its resulting temperature.
2. Approximate the curve of figure 13-2 with a straight line. What is the y-intercept? What is the slope?
3. Write an equation for the line you drew in problem 2. The equation for a straight line is $Y = mx + b$ where m is the slope and b is the y-intercept.
4. Explain with the aid of diagrams how the thermistor could be used to control the furnace in your home.
5. Briefly explain how a thermistor connected to the evaporator coils of an air conditioner in your car could be used to prevent icing.

experiment 14 TEMPERATURE CONTROL COUNTER

INTRODUCTION. Digital control systems often employ counting as an error detection system. In this experiment we will examine integrated circuit counting and how it can be utilized as an error measuring device.

DISCUSSION. A basic digital control system is represented by the block diagram of figure 14-1. It is a closed-loop digital servomechanism. The clock of figure 14-1 tells the counter *how long* to count the pulses from the variable frequency oscillator. Since this is a fixed time determined by the clock, the number of cycles from the variable frequency oscillator occurring during this time is an indication of the condition of the controlled device. This is because the controlled device is being used to determine the frequency of the variable frequency oscillator.

If the count that accumulates in the counter during a cycle of the clock is the predetermined correct amount, the controller does nothing. However, if the count is wrong, the controller would be activated to correct the error. This would then produce the correct count, stopping the controller. The general description fits the concept of a closed-loop servomechanism where a count of the pulses is used in error sensing.

In this experiment we are going to concentrate on the counter and its application in

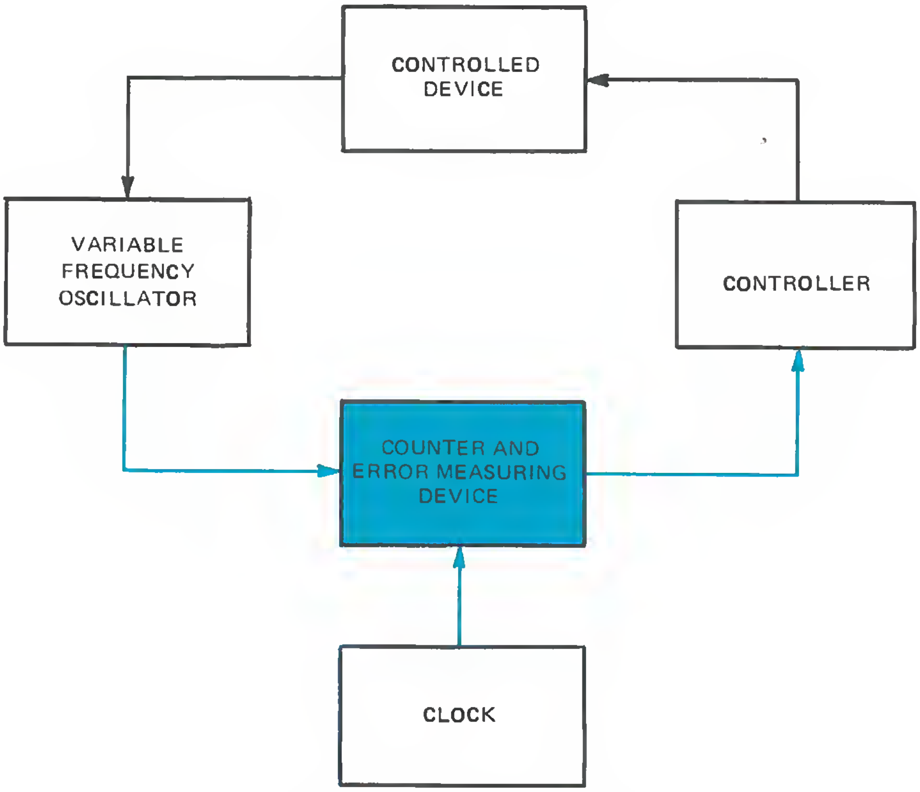


Fig. 14-1 A Digital Control System

BINARY				DECIMAL
2^3	2^2	2^1	2^0	
0	0	0	0	0
0	0	0	1	1
0	0	1	0	2
0	0	1	1	3
0	1	0	0	4
0	1	0	1	5
0	1	1	0	6
0	1	1	1	7
1	0	0	0	8
1	0	0	1	9
1	0	1	0	10
1	0	1	1	11
1	1	0	0	12
1	1	0	1	13
1	1	1	0	14
1	1	1	1	15

Fig. 14-2 Binary Counting

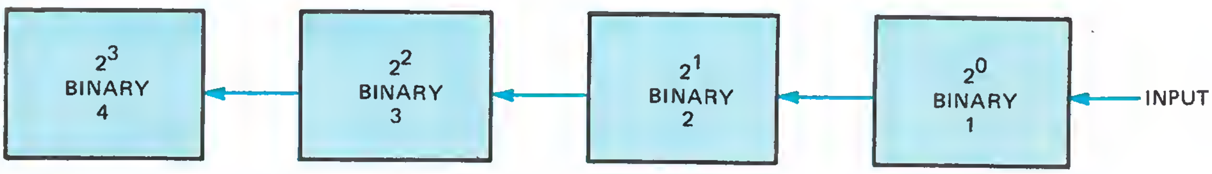


Fig. 14-3 Binary Counter

such a system. We are going to use two integrated circuits with a two-bit binary counter in each one. This will give us a four-bit binary counter. To review the operation refer to the table of figure 14-2.

Each time a pulse comes into the four-stage counter it advances to the next count. To represent this counter with minimum confusion, the *units* digit counter is shown on the right and the 2^3 digit is shown on the left. This makes the count correspond to the table but makes the signal go from right to left, which is reverse to the conventional signal flow in circuit diagrams.

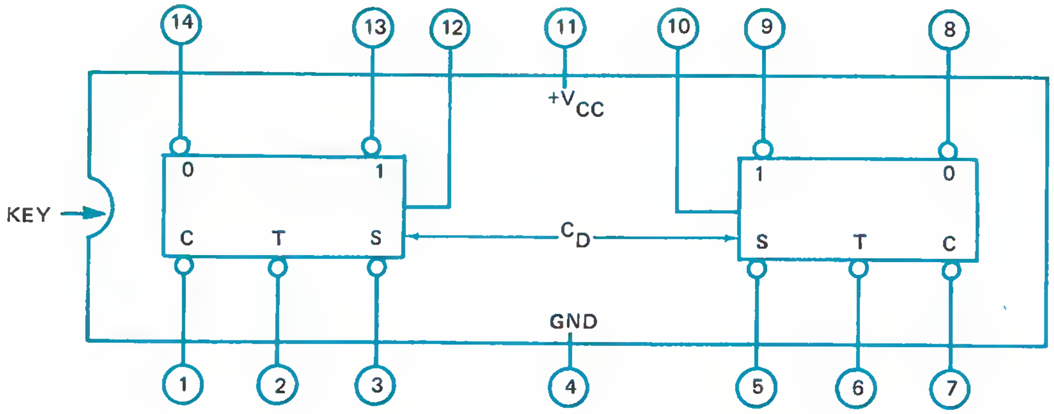


Fig. 14-4 Top View of the MC 790P

The binary counter to be used in this experiment is shown in figure 14-4. You will recognize it as two J-K flip-flops in one package. Pins 10 and 12 are the DC clear pins, C_D.

In order to observe the counting action by manual operation, it will be necessary to use a monostable multivibrator to eliminate false counting caused by switch contact bounce. The monostable remains in its stable condition until pulsed (in the case of this experiment, by pushing a switch), at which time the monostable switches to its unstable state and remains there for a period of time, then returns to its stable condition. The monostable is composed of the two NOR circuits on the left side of figure 14-5. Note that the circuit of figure 14-5 has a signal flow from left to right, which places the units digit on the far left.

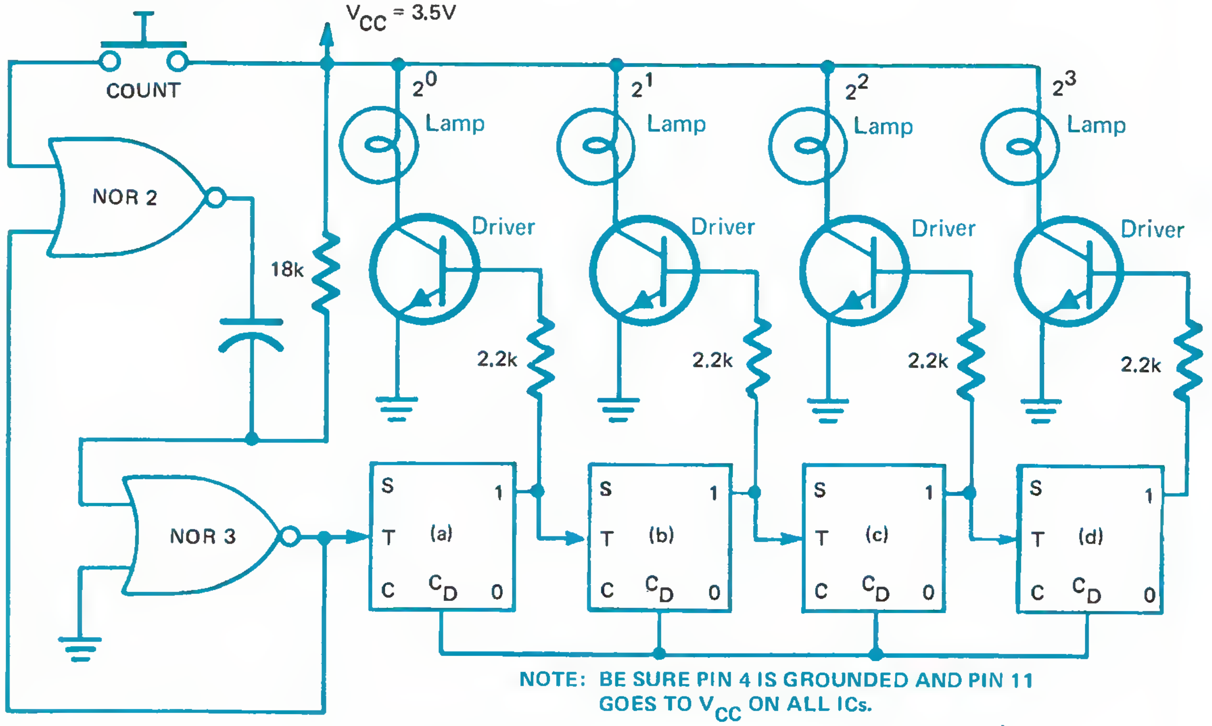


Fig. 14-5 Experimental Circuit

MATERIALS

1 Integrated circuit, type MC 790P or equivalent
1 Integrated circuit, type MC 724P or equivalent
1 Capacitor, 10 μF, 6V DC
3 Resistor substitution boxes
2 Resistors, 2.2 kΩ, 1/2W
1 Switch, pushbutton, normally open
4 Lamps, 3V, #48 or equivalent with sockets
4 Transistors, 2N3709 or equivalent NPN general purpose type
1 DC power supply (0 - 40V)

PROCEDURE

1. Connect the circuit shown in figure 14-5.
2. Apply power and momentarily connect the DC reset line, C_D, to the 3.5-volt supply. All lamps should be out. A lighted lamp is a 1 and an unlighted lamp is a 0, so the first entry line in the data table would be all zeros as shown.
3. Press the count button one time and enter the results in the data table. **Remember that the table and circuit are laid out in reverse so that a lamp lighted on the far left enters as a one on the right of the data table.**
4. Repeat step three until the first data table is complete.
5. Zero the counter by applying V_{CC} to the C_D line.
6. Connect the 1 output of stage (d) to the S input of stage (a).
7. Press the count button once and enter the results in the second data table.
8. Repeat step seven until the data table is complete. The circuit is supposed to stop counting part way through.

ANALYSIS GUIDE. Explain the circuit operation and tell why the count was different in the second data table from that in the first.

PROBLEMS

1. Draw the block diagram of the four-stage binary counter with the trigger input to the first stage being fed by a 2-input AND. Explain the circumstances under which the binary counter will receive something to count.
2. Suppose one input to the AND gate of problem 1 is being fed a 500-Hz signal, the other input is grounded. What will the counter do?
3. If a pulse of 0.01 sec duration is fed to input 2 while the 500-Hz signal is being fed to input 1, what would the counter read in binary? Assume the counter to be zeroed initially.

4. If the pulse duration of problem 3 were 0.04 seconds, what would the counter have read in binary?

5. Show a connection so that the counter would only count to 8.

6. Show a counter that would stop at 12. Use a 2-input AND circuit to stop the count.

BINARY				DECIMAL
(d)2^3	(c)2^2	(b)2^1	(a)2^0	
0	0	0	0	0
				1
				2
				3
				4
				5
				6
				7
				8
				9
				10
				11
				12
				13
				14
				15

Fig. 14-6 The Data Tables

BINARY				DECIMAL
(d)2^3	(c)2^2	(b)2^1	(a)2^0	
0	0	0	0	0
				1
				2
				3
				4
				5
				6
				7
				8
				9
				10
				11
				12
				13
				14
				15

Fig. 14-6 The Data Tables (Cont'd)

experiment 15 AUTOMATIC TEMPERATURE CONTROL

INTRODUCTION. Digital servo systems are used to control a variety of industrial processes. In this experiment we will investigate a simplified example of a working digital closed-loop servomechanism.

DISCUSSION. The block diagram of one type of digital control system is shown in figure 15-1.

The clock in figure 15-1 tells the counter *how long* to count the pulses from the variable frequency oscillator. Since this is a fixed time determined by the clock, the number of cycles from the variable frequency oscillator occurring during this time is an indication of the condition of the controlled device. This is because the controlled device is being used to determine the frequency of the variable frequency oscillator.

If the count that accumulates in the counter during a cycle of the clock is the predetermined correct amount, the controller does nothing. However, if the count is wrong, the controller would be activated to correct

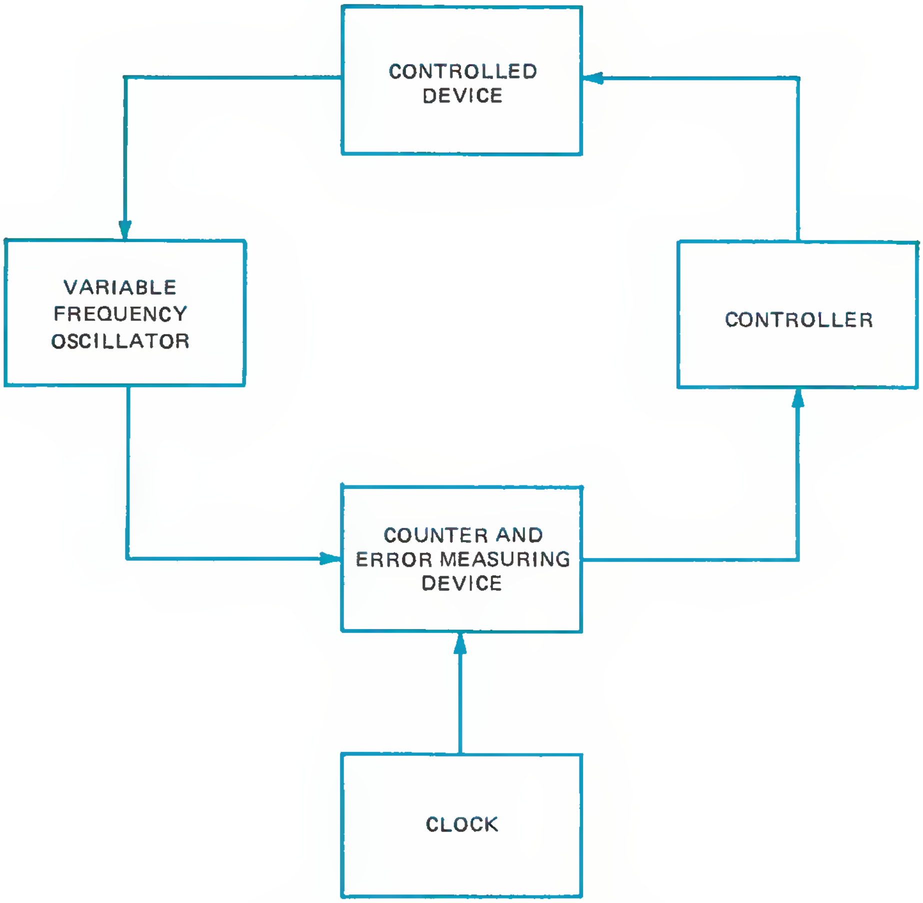


Fig. 15-1 A Digital Control System

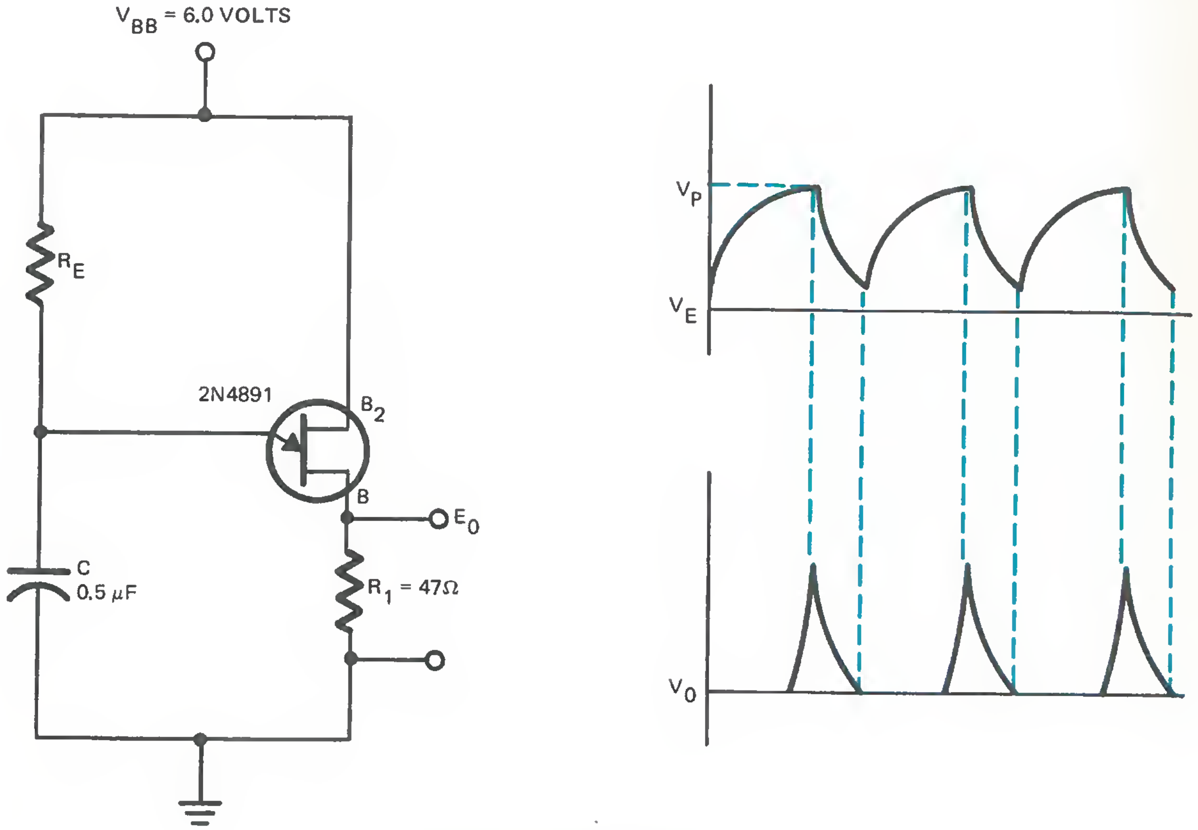


Fig. 15-2 UJT Oscillator

the error which would subsequently produce the correct count, stopping the controller.

A variable frequency oscillator employing a UJT will serve as the pulse source in this experiment. Figure 15-2 shows the circuit diagram that we will use.

The firing or peak voltage, V_p, of the UJT is given by

$$V_p = \eta V_{BB}$$

where η is the intrinsic standoff ratio (a constant for any given UJT which varies from about 0.5 to 0.85 for most devices) and V_{BB} is the supply voltage.

Once the capacitor charges to this voltage the UJT "fires", allowing the capacitor to discharge through R_1 and the base one - emitter circuit, generating the output voltage shown. The output frequency, f, is given approximately by

$$\boxed{f \cong \frac{1}{R_E C}}$$

where R_E is the total emitter resistance.

For the control system that we are going to use, the emitter resistance will be replaced by a thermistor so that as the temperature varies, the frequency of the variable frequency oscillator will change.

The circuit of figure 15-3 is a collector-coupled astable multivibrator. The circuit diagram and integrated circuit layout are shown

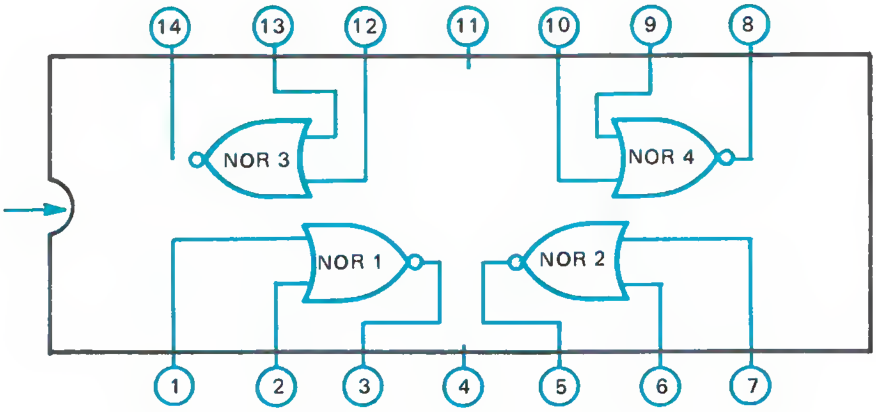


Fig. 15-3(A) Top View of One IC to be Used

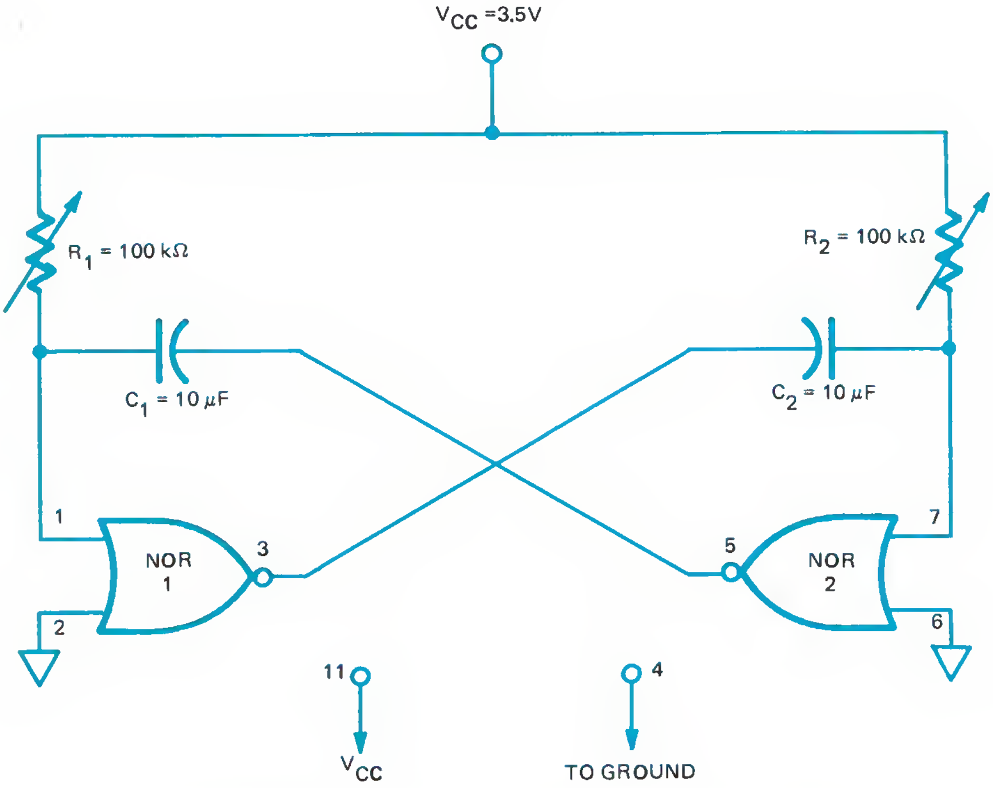


Fig. 15-3(B) An Integrated Astable Multivibrator Clock

in figure 15-3. The output frequency, f, is given approximately by

$$\boxed{f \cong \frac{1}{1.4RC}}$$

where the output is a symmetrical wave.

The desired waveform is one that is similar to the one shown in figure 15-4.

The controlled device in the system will be an oven employing a lamp as the heating element. It is shown in figure 15-5. The SCR controls the lamp which heats the oven and

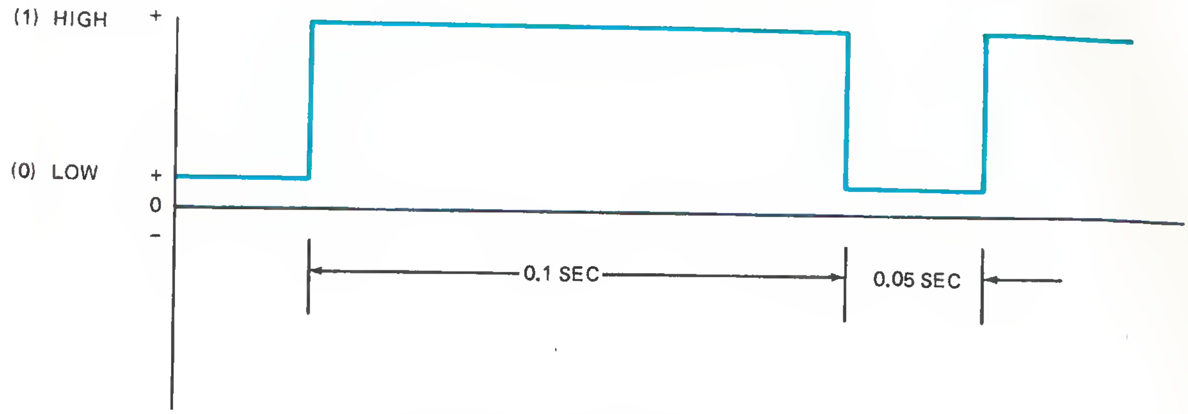


Fig. 15-4 Clock Waveform

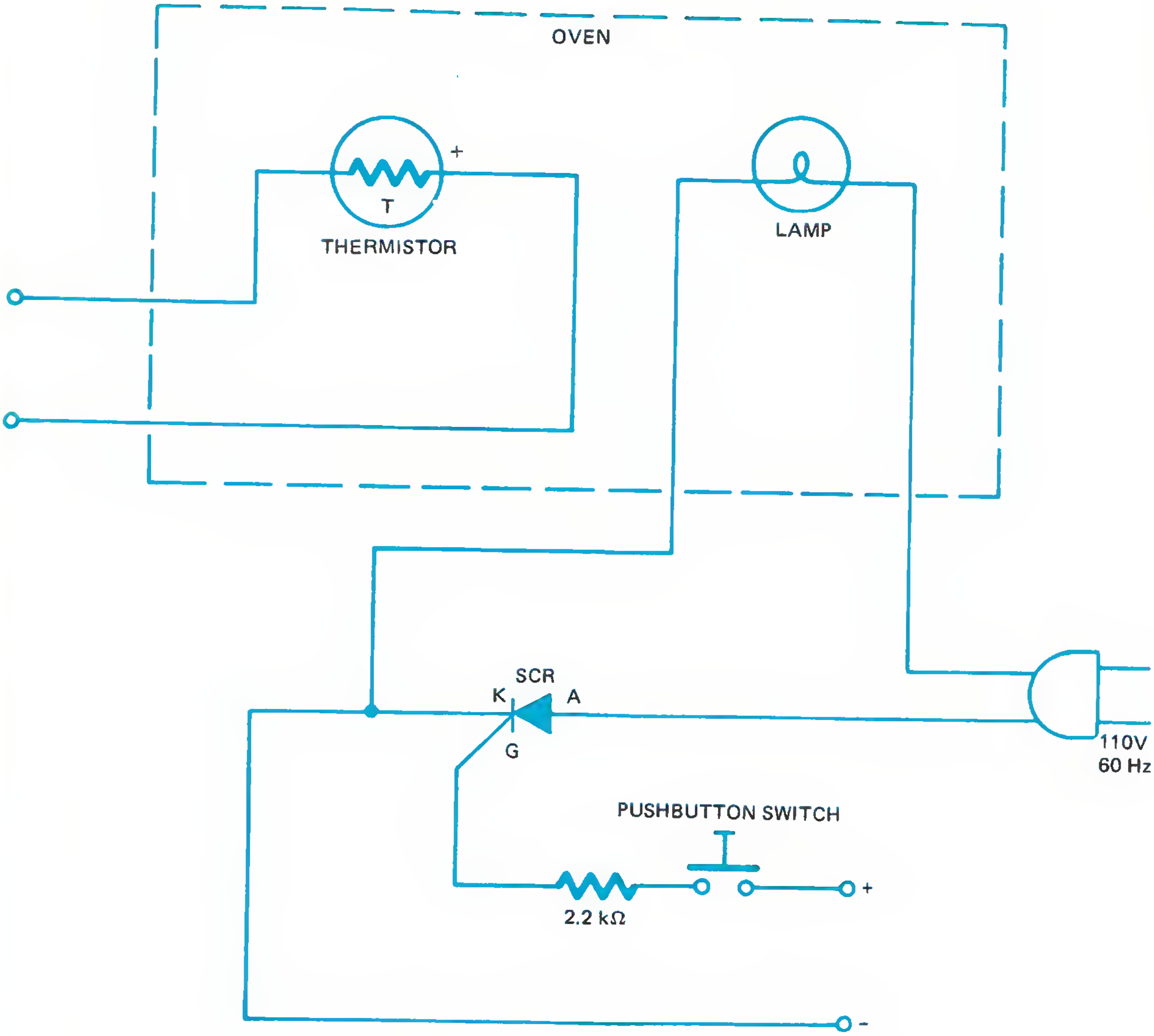


Fig. 15-5 The Controller and Controlled Device

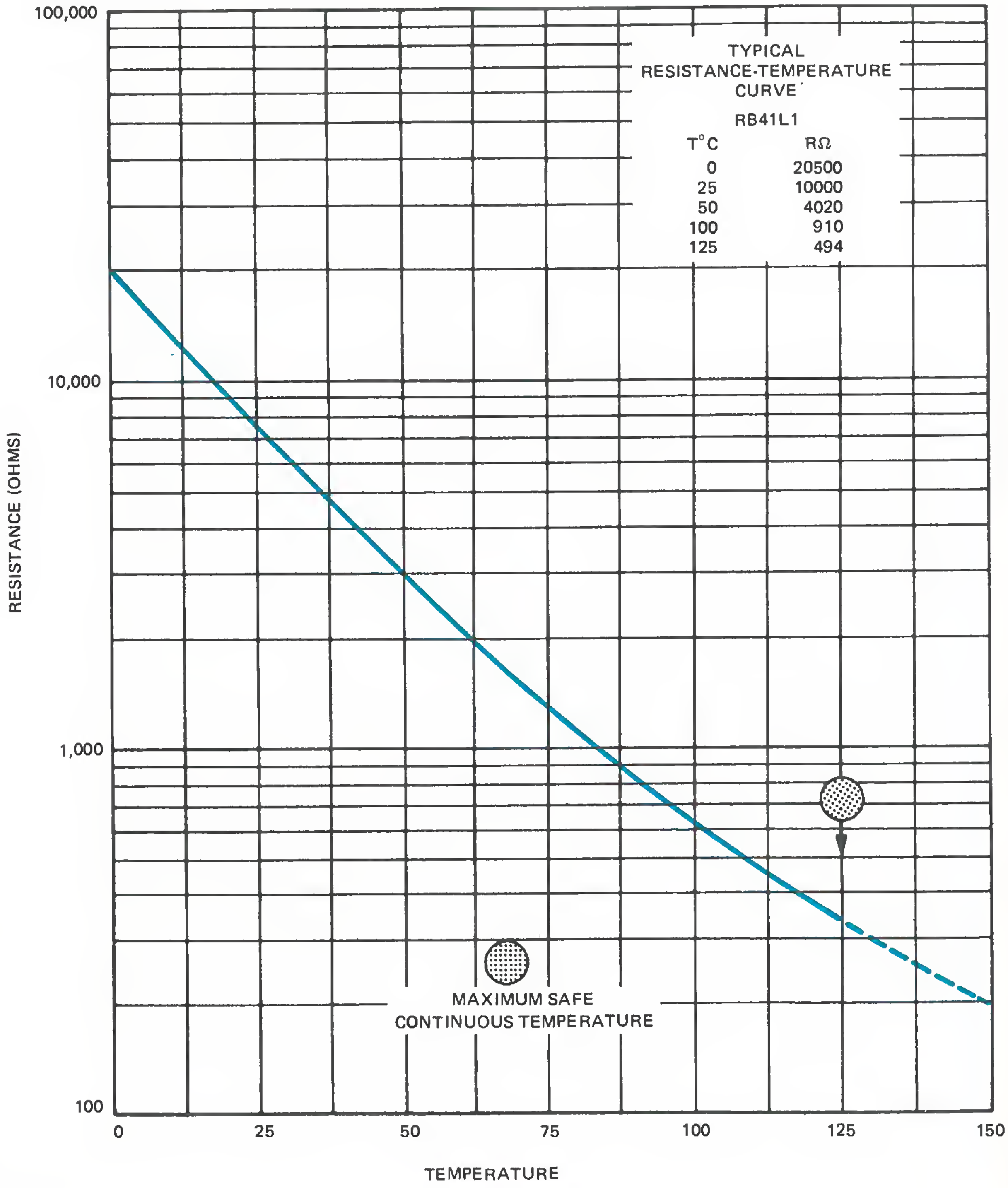


Fig. 15-6 Thermistor Curve

varies the resistance of the thermistor. The thermistor response to temperature is shown in figure 15-6.

The counter that we will use in this experiment is a four-bit counter like the one shown in figure 15-7.

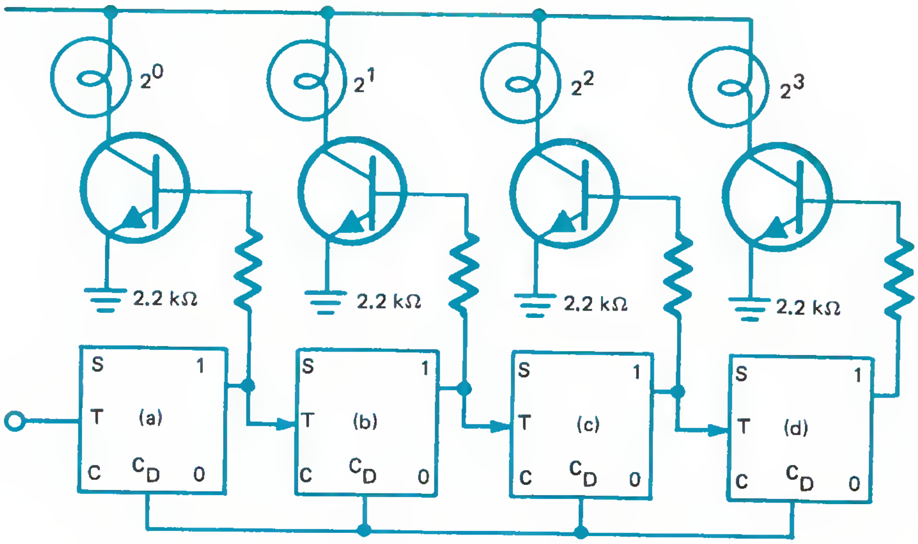


Fig. 15-7 Binary Counter

MATERIALS

- 2 Potentiometers, 10 kΩ, 2W, linear, or decade resistance box
- 1 Capacitor, 0.5 μF, 6V
- 1 UJT transistor, type 2N4891 or equivalent
- 1 Resistor, 1 kΩ, 1/2W
- 1 Resistor, 47Ω, 1/2W
- 1 DC power supply (0 – 40V)
- 1 Oscilloscope
- 1 Quad, 2-input NOR integrated circuit, MC 724P or equivalent
- 2 Capacitor substitution boxes
- 1 Capacitor, 0.5 μF, 10V DC
- 2 Potentiometers, 100 kΩ, 1/2W, linear, or decade resistance box
- 1 Oven (use a cardboard box such as a shoe box)
- 1 Resistor substitution box
- 1 Lamp with socket, 75W, 115V
- 1 Thermistor, bead type, 10 kΩ, type RB41L1 or equivalent
- 1 Pushbutton SPST switch
- 4 Resistors, 2.2 kΩ, 1/2W
- 1 SCR, GE C22B or equivalent
- 1 Line cord
- 1 VOM or FEM
- 2 Integrated circuits, type MC 790P or equivalent
- 1 Resistor, 18 kΩ, 2W
- 4 Lamps with sockets, 3V, #48 or equivalent
- 4 NPN transistors, type 2N3709 or equivalent, general purpose

PROCEDURE

1. Figure 15-8 shows the waveform of (a) the variable frequency oscillator and (b) the clock, for comparison. They are not shown to actual scale.

2. The (c) part of figure 15-8 illustrates what is desired to go into the counter. The number of pulses let in during time periods 1 and 3 will be an indication of temperature since temperature controls the UJT oscillator. (Note: This can be accomplished with an AND circuit.)

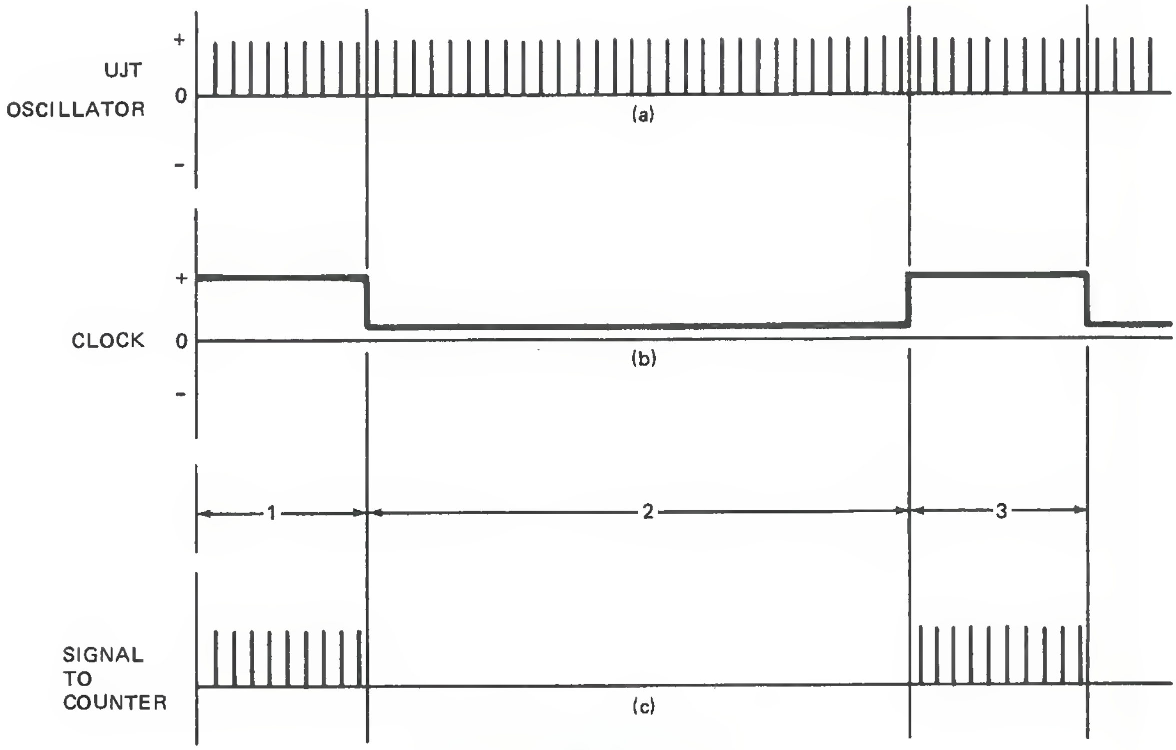


Fig. 15-8 Waveforms

3. Time period 3 is the time for the light to be ON or OFF depending upon the temperature.

4. For this experiment we want to arrange the circuit so that the light will go OFF if the counter reaches a count of digital 8 (binary 1000). This can be accomplished by connecting the 0 output (d) of the binary counter to the gate of the SCR (see figure 15-7). This will turn the SCR OFF when the count of 8 is reached and thus turn the light OFF. If 8 is not reached, the light will remain ON.

5. A positive pulse on the C_D line will zero the counter. Thus, it will be necessary to differentiate the waveform of figure 15-8(b) so that a positive spike at the *beginning* of time periods 1 and 3 will zero the counter.

6. To prevent a higher frequency from counting on past zero, connect the 1 output of (d) of the binary counter to the S input of (a).

7. Use the thermistor curve to determine the resistance at 150°F. Calculate the frequency of the UJT using this resistance as the emitter resistor.

8. Calculate the pulse width needed for time intervals 1 and 3, etc., to let 8 pulses enter the counter at 150°F.

9. Apply power to the clock and adjust for the appropriate time interval. Intervals where the lamp is lighted are not critical in time length.

10. Connect the circuit as in figure 15-9 and measure the temperature in the box after the lamp goes out.

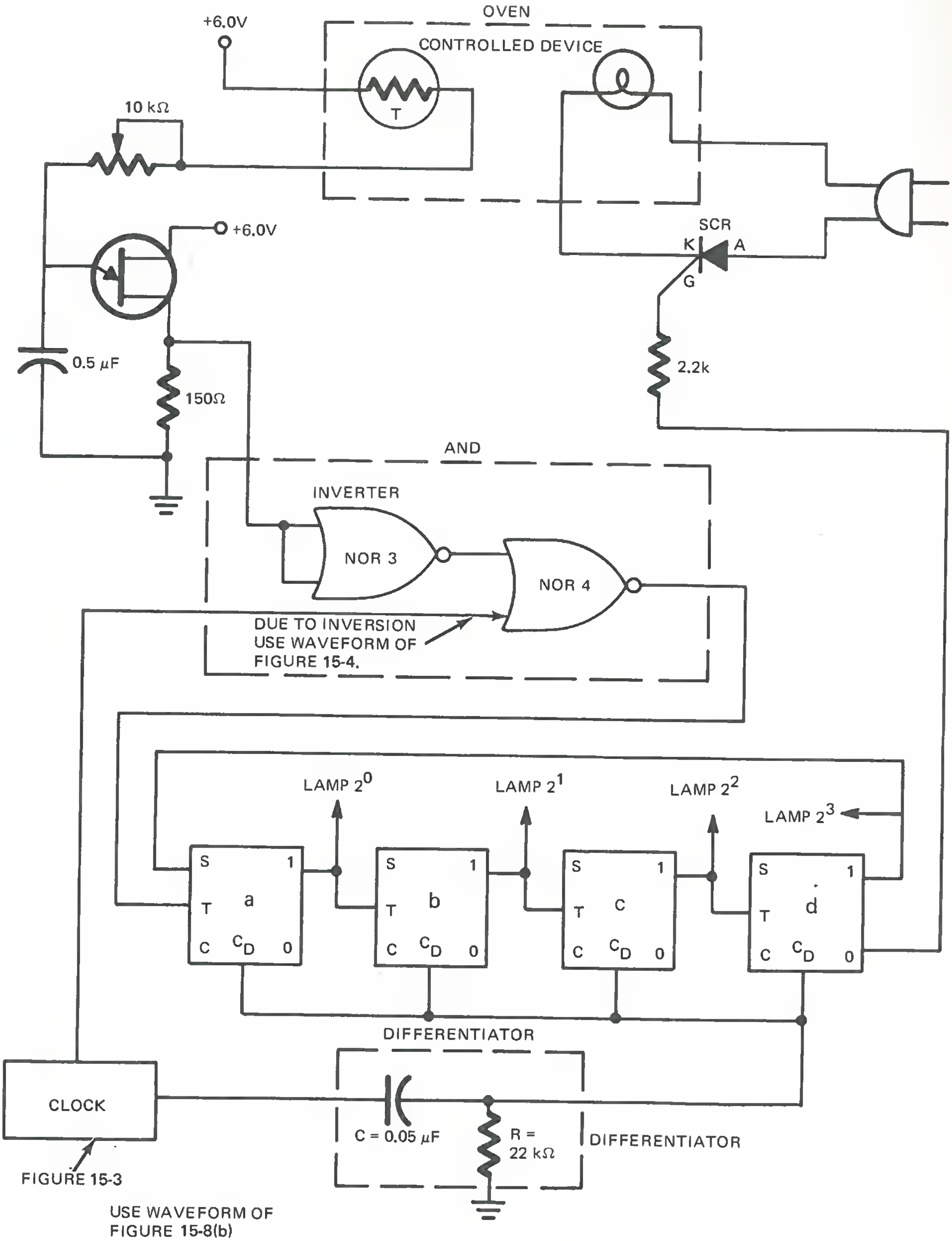


Fig. 15-9 Experimental Setup

ANALYSIS GUIDE. Explain the circuit operation.

PROBLEMS

1. Determine the necessary changes to regulate the temperature at 200°F.
2. Repeat problem 1 for a temperature of 250°F.

EXPERIMENT 1 ____________ Name ____________

Date: ____________ Class ________ Instructor ________

Rotor Position	E_{R1}	E_{R2}	E_{R3}	E_{S2-S1}	E_{S2-S3}	E_{S3-S1}
0°						
45°						
90°						
135°						
180°						
225°						
270°						
315°						

Fig. 1-10 The Data Table

Scope Recording

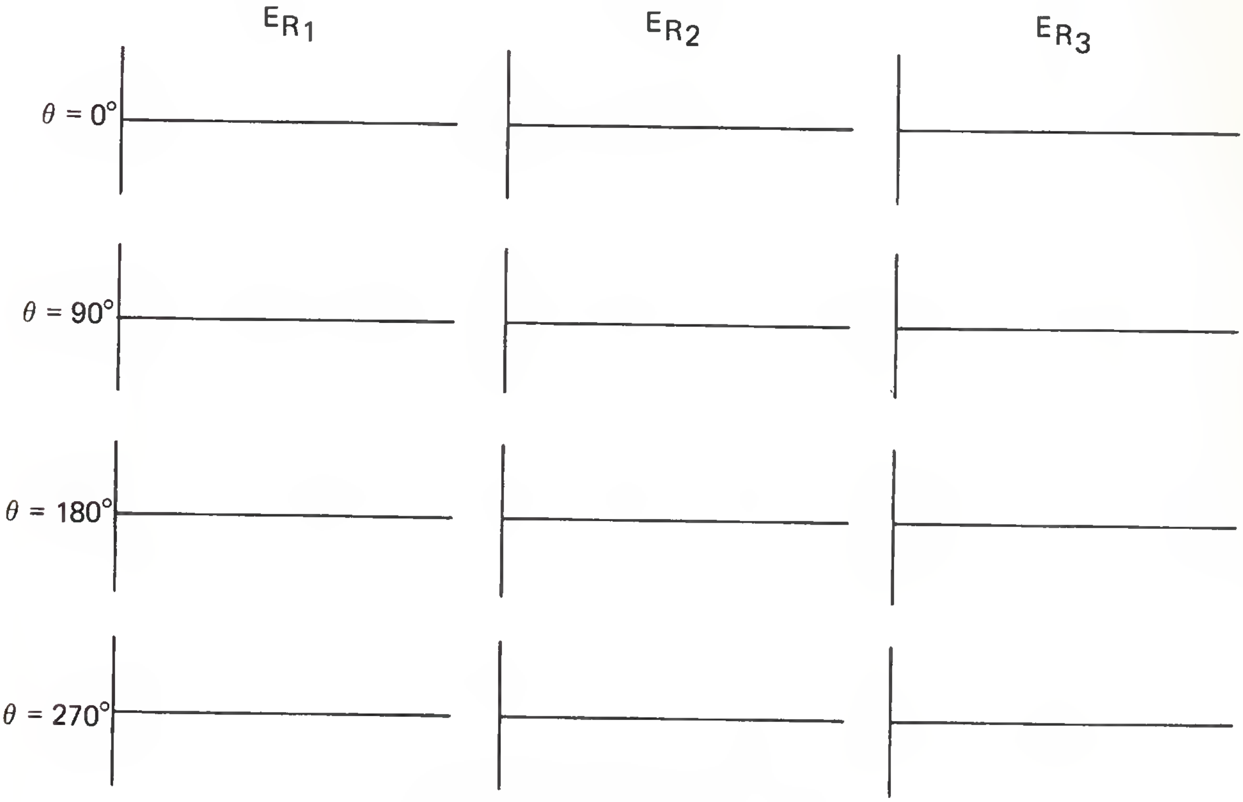


Fig. 1-10 The Data Tables (Cont'd)

EXPERIMENT 2 ______________ Name ______________________________

Date: ______________________ Class __________ Instructor ______________

Transmitter Rotor - θ_T	Receiver Steps 4&5 - θ_R	Receiver Step 6 - θ_R	Receiver Step 7 - θ_R	Receiver Step 8 - θ_R	Receiver Step 9 - θ_R
0°					
45°					
90°					
135°					
180°					
-45°					
-90°					
-135°					
-180°					

Receiver Torque ______________________________

Fig. 2-12 The Data Table

EXPERIMENT 3

Name ______________________

Date: ______________________ Class ____________ Instructor ______________

Transmitter Angle Θ_i	0° Transformer Output e_o		30° Transformer Output e_o		330° Transformer Output e_o	
	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
0°						
60°						
120°						
180°						
-60°						
-120°						
-180°						

Fig. 3-5 The Data Table

EXPERIMENT 4

Name ______________________

Date: ______________________

Class ____________ Instructor ______________

$\beta = 45°$

α	γ
0°	
90°	
180°	
-90°	
-180°	

$\beta = 45°$

α	γ
0°	
90°	
180°	
-90°	
-180°	

For Fig. 4-7

$\beta = 270°$

α	γ
0°	
90°	
180°	
-90°	
-180°	

$\beta = 270°$

α	γ
0°	
90°	
180°	
-90°	
-180°	

For Fig. 4-8

$\beta = 45°$

0°	
90°	
180°	
-90°	
-180°	

$\beta = 270°$

0°	
90°	
180°	
-90°	
-180°	

For Fig. 4-9

Steps 7 & 8

		β
45°	45°	
90°	180°	
180°	270°	
270°	360°	
360°	90°	

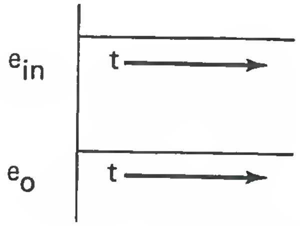
For Fig. 4-9

Fig. 4-10 The Data Table

EXPERIMENT 5 Name ______________________

Date: ______________________ Class ____________ Instructor ______________

θ_i	θ_o	θ_i	θ_o
0°		120°	
60°		300°	
120°			
180°			
240°			
300°			
360°			



$$\frac{N_m}{N_{CT}} = \_\_\_\_\_\_\_\_\_\_$$

$$\frac{N_m}{N_{Dial}} = \_\_\_\_\_\_\_\_\_\_$$

Fig. 5-8 The Data Table

Direction of rotation ______________________

$S_1 \rightarrow S_1$

$S_2 \rightarrow S_2$

$S_3 \rightarrow S_3$

Direction of rotation ______________________

$S_1 \rightarrow S_3$

$S_2 \rightarrow S_2$

$S_3 \rightarrow S_1$

Fig. 5-8 The Data Table (Cont'd)

EXPERIMENT 6

Date: ______________________

Name ______________________

Class ____________ Instructor ______________

Angle θ (degrees)	Sin-Cos Pot.		Triangular Potentiometer
	pin 2	pin 4	
0			
20			
40			
60			
80			
90			
100			
120			
140			
160			
180			
200			
220			
240			
260			
270			
280			
300			
320			
340			
360			

Fig. 6-6 The Data Table

Output	
pin 2	+ 0 –
pin 4	+ 0 –
triangular	+ 0 –

Fig. 6-6 The Data Table (Cont'd)

EXPERIMENT 7

Name ______________________________

Date: ____________________ Class ____________ Instructor ______________

EXPERIMENT 8 Name ____________________

Date: ____________________ Class ____________ Instructor ____________

Control (DC)				Controlled (AC Load)				
	Current	Voltage	Power	Current	Voltage	Power	Waveform	Power Gain
1								
2								
3								

Results of Step 6:
Results of Step 7:

Fig. 8-10 Data Tables

Results of step 12:

Control (Field)				Controlled (Armature)			Results
	Voltage	Current	Power	Voltage	Current	Power	Power Gain
1					0.5 A		
2					1.0 A		
3					1.5 A		
4							

Fig. 8-10 The Data Tables (Cont'd)

EXPERIMENT 9

Name ______________________________

Date: ____________________ Class __________ Instructor ______________

Input Shaft Angle	Output Shaft Angle
0°	0°
30°	
60°	
90°	
120°	
150°	
180°	
210°	
240°	
270°	
300°	
330°	
360°	

Dead Band ____________________

Output Torque: 5° error ______ in.-oz
10° error ______ in.-oz
15° error ______ in.-oz

Fig. 9-3 The Data Table

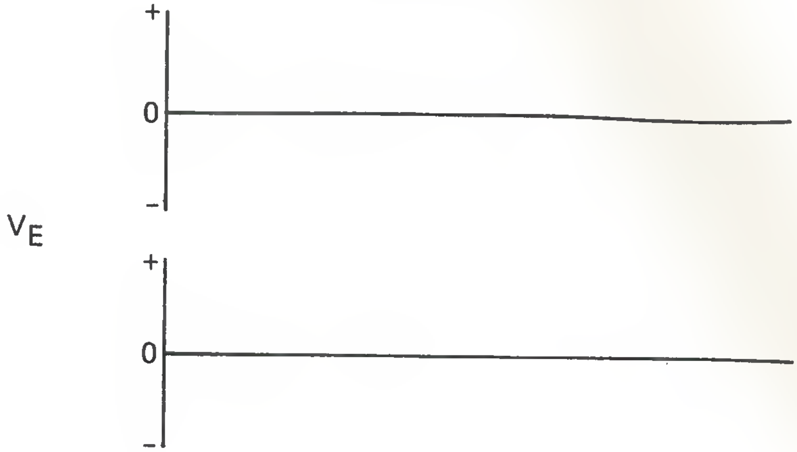
EXPERIMENT 10 ______________ Name ______________________________________

Date: ____________________________ Class __________ Instructor ____________________

EXPERIMENT 11 | Name ______________________

Date: ______________________ | Class __________ Instructor ______________

Waveshapes (Fig. 11-2)



R_E	Calculated Frequency	Measured Frequency
1 kΩ		
2 kΩ		
4 kΩ		
8 kΩ		
10 kΩ		
12 kΩ		
14 kΩ		
16 kΩ		
18 kΩ		
20 kΩ		

Fig. 11-3 The Data Table

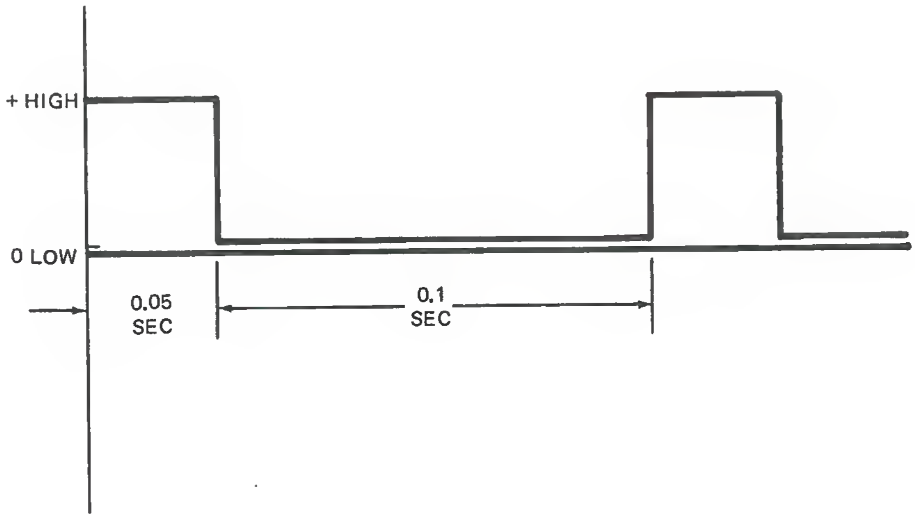
EXPERIMENT 12 Name ______________________

Date: ______________ Class __________ Instructor __________

Input A (pin 1)	Input B (pin 2)	Output (pin 3)
0	0	
0	3.5	
3.5	0	
3.5	3.5	

A	B	Output
0	0	
0	1	
1	0	
1	1	

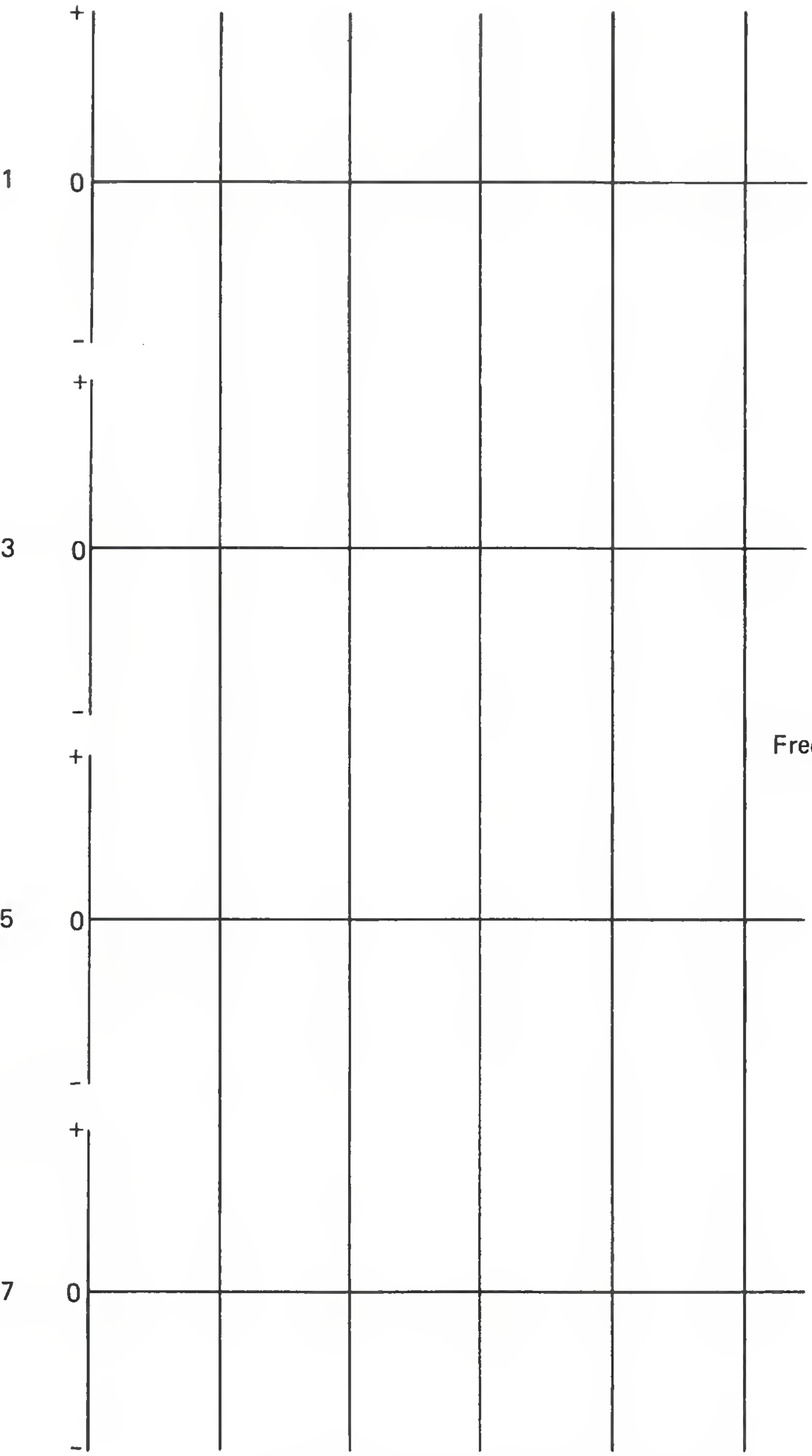
Fig. 12-6 Data for the NOR Logic



R_1 = ______________ ohms

R_2 = ______________ ohms

Fig. 12-8 Data for Nonsymmetrical Output



Frequency = ________ Hz

Fig. 12-7 Data Table for Multivibrator

EXPERIMENT 13 Name ____________________

Date: ____________ Class ________ Instructor ____________

Time	Thermistor Resistance	Temperature
10 sec		
30 sec		
50 sec		
60 sec		
2 min		
3 min		

Fig. 13-4 The Data Table

EXPERIMENT 14 Name ____________________

Date: ____________________ Class ____________ Instructor ____________________

BINARY				DECIMAL
(d)2^3	(c)3^2	(b)2^1	(a)2^0	
0	0	0	0	0
				1
				2
				3
				4
				5
				6
				7
				8
				9
				10
				11
				12
				13
				14
				15

Fig. 14-6 The Data Tables

BINARY				DECIMAL
$(d)2^3$	$(c)2^2$	$(b)2^1$	$(a)2^0$	
0	0	0	0	0
				1
				2
				3
				4
				5
				6
				7
				8
				9
				10
				11
				12
				13
				14
				15

Fig. 14-6 The Data Tables (Cont'd)

EXPERIMENT 15

Name ______________________

Date: ______________ Class __________ Instructor ______________